REPORT NO. FRA/TTC-80/05 PB

MASSACHUSETTS BAY TRANSPORTATION AUTHORITY BLUE LINE VEHICLE EVALUATION

TRANSPORTATION TEST CENTER
FEDERAL RAILROAD ADMINISTRATION
Pueblo, Colorado 81001

MASSACHUSETTS BAY TRANSPORTATION AUTHORITY
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FINAL REPORT

JULY 1980

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16. Abstract

The report presents the results of engineering tests carried out on a pair of rapid transit cars for the Massachusetts Bay Transportation Authority. The tests were performed at the Transportation Test Center, Pueblo, Colorado, from April 1979 through October 1979. The scope of the test program included an evaluation of performance, ride quality, and interior and wayside noise, using standardized test procedures; special engineering tests were made to evaluate energy conservation methods and three types of experimental brake shoes.

The tests showed that the vehicles met their design specification requirements with some deficiencies, notably in emergency braking rates. An energy conservation technique was evaluated, in which response characteristics of the vehicle propulsion system were modified to reduce energy needs due to aerodynamic drag at high speeds. Several potential energy-saving configurations were identified, with minimal impact on round-trip times. The experimental brake shoes tested were found to give performance comparable to the original equipment at normal operating speeds for the MBTA Blue Line, but were inferior at higher speeds.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	sq inches	6.5	sq centimeters	cm^2
ft^2	sq feet	0.09	sq meters	m^2
yd^2	sq yards	0.8	sq meters	m^2
mi^2	sq miles	2.6	sq kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (after subtracting 32)	Celsius	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	sq centimeters	0.16	sq inches	in^2
m^2	sq meters	1.2	sq yards	yd^2
km^2	sq kilometers	0.4	sq miles	mi^2
ha	hectares (10,000 m)	2.5	acres	a
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic	ft
m^3	cubic meters	1.3	cubic	yd
		TEMPERATURE (exact)		
°C	Celsius	9/5 (then add 32)	Fahrenheit	°F

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ACRONYMS

ACT-1	Advanced Concept Train-1
CCW	counterclockwise
CTA	Chicago Transit Authority
CTS	Cleveland Transit System
CW	clockwise
EP	electro-pneumatic (braking)
FM	frequency modulation
FRA	Federal Railroad Administration
GVTP	General Vehicle Test Plan
IRIG-B	Inter Range Instrumentation Group time code format B
ISO	International Standards Organization
MBTA	Massachusetts Bay Transportation Authority
NYCTA	New York City Transit Authority
R&D	Reseach and Development
SAP	straight air pipe (braking)
TTC	Transportation Test Center
TTT	Transit Test Track
UMTA	Urban Mass Transportation Administration
WMATA	Washington Metropolitan Area Transit Authority

ABBREVIATIONS

A	ampere
B&K	Bruel & Kjaer
dB	decibel
dBA	decibel, A-weighted
°	degree, Fahrenheit
d.c.	direct current
',ft	foot
g	gravity
h	hour
Hz	Hertz
",in	inch
kW	kilowatt
m	meter
mi	mile
N	Newton
%	percent
PSD	Power Spectral Density
psig	pounds per square inch gage
rms	root mean square
s	second
v	volt

EXECUTIVE SUMMARY

In 1973, specifications for 70 new cars for the Blue Line and 120 new cars for the Orange Line were released by the Massachusetts Bay Transportation Authority (MBTA). The original specifications were rewritten to provide greater similarity between the two designs, and were reissued in 1974. A contract was signed on August 29, 1976, with Hawker-Siddeley Canada Ltd., for production of the new vehicles. The MBTA, in cooperation with the Urban Mass Transportation Administration (UMTA), requested that the Federal Railroad Administration (FRA) conduct engineering tests on a married pair of production Blue Line vehicles. These tests were conducted from April through October 1979 at the Transportation Test Center (TTC). This report documents the results of those tests.

The tests were directed by UMTA with the MBTA providing a project engineer from the consulting firm of Louis T. Klauder & Associates for technical coordination. The TTC provided technical support and carried out a series of standardized test procedures to characterize the vehicles. Special Engineering tests were carried out to MBTA direction to resolve problems of interest to the transit property. L.T. Klauder provided the detailed test procedures, and the TTC provided instrumentation hardware, instrumentation setup and operation, vehicle operation, maintenance and repair, and carried out data reduction and reporting. Hawker-Siddeley engineers provided technical support throughout the test program.

The purpose of the tests was to evaluate the MBTA Blue Line vehicles in selected areas of performance, ride quality, and wayside and onboard noise. Additional tests were conducted with experimental brake shoes, and with variations of the propulsion system characteristics in order to define energy saving configurations. Truck frame and traction motor vibration were monitored during ride quality tests, and coupler noise was investigated. The test results provide valuable information for determining that the vehicles delivered to MBTA comply with specification requirements, establishing MBTA operation and maintenance policies, establishing and upgrading future vehicle specifications, and future vehicle development efforts.

The controlled test conditions at the TTC expedited the testing procedure and avoided competition with revenue service for track time and manpower. The extensive nature of the TTC facilities and the familiarity of the staff with the test procedures enabled the MBTA to perform tests that would have been impractical to run on their own property.

The two test vehicles, serial numbers 0608 and 0609, were built to MBTA specification "Equipment Engineering No. 590, No. 4 East Boston Rapid Transit Cars." The vehicle bodies are welded steel structures, fabricated from high tensile, low alloy steel. They are mounted on two double-axle, General 70-type equalized trucks with inside journals. The truck frames are one-piece cast steel fabrications; cast sections are welded together to form the frame in a unique cast-weld process. Primary suspension is provided by rubber chevron springs with an air spring secondary suspension. The trucks are load-compensated to provide a constant floor height of 41.5" above the rail. The axles are fitted with 28" wheels.

The traction motors are 4-pole d.c. series wound units and are suspended from rubber cushioned hangers. The two motors on each truck are connected in series, and are designed for a nominal 300 V operation (600 V line). Parallel-type reduction gearing provides a 6.13:1 reduction from the motors to the axles. The propulsion control system is conventional in design, with four basic traction motor power configurations, controlled by a cam controller. Logic circuits compensate for variation in vehicle gross weight to provide constant acceleration and deceleration levels. The major braking effort of the car is provided by the dynamic braking capability of the propulsion system, supplemented by electro-pneumatic tread brakes. The tread brakes also provide a backup system if dynamic braking should fail.

Track tests were conducted on the Transit Test Track (TTT), a 9.1-mi oval of FRA Class 6 track. The married vehicle pair were representative of vehicles used in revenue service on the Blue Line; they were tested in a standard configuration with the exception of onboard instrumentation, motor shrouds, and special controller settings. Test speeds ranged from 0 to 65 mi/h. Passenger loading was simulated by the weight of onboard instrumentation and lead ballast distributed on the floor of the cars.

Standard tests were conducted in accordance with the General Vehicle Test Plan (GVTP), which defines guidelines and methods for testing and evaluating transit vehicles in the areas of performance, ride quality, and wayside and onboard noise.

Special braking tests were conducted on three experimental brake shoe types provided by different manufacturers. Special energy consumption tests were also conducted to evaluate the potential energy savings available with various control system configurations. Test runs were made using a simulation of the MBTA Blue Line revenue profile, with 22 station stops.

Vibration data for the truck frame and traction motor assembly were collected during the ride quality test runs, and were used to supplement the ride quality data. An assessment was made of the transmissibility of vibrations through the axle journals to the truck and through the secondary suspension to the carbody.

Coupler noise observed during the tests was investigated using closed-circuit television and displacement transducers to record the movement of the coupler under load. The test data indentified a series of cumulative machining tolerances, which led collectively to excessive clearance in the draft gear assemblies. This clearance resulted in coupler noise under run-in and runout conditions.

The performance tests showed that the Blue Line vehicles met most of the specification compliance criteria for acceleration and braking. The maximum average acceleration achieved (2.4 mi/h/s) fell marginally below the specification requirement of 2.5 mi/h/s; the vehicles required 26.3 seconds to reach 40 mi/h with a rush hour passenger load, slightly more than the specification requirement of 25 seconds; they were well under the specification requirement to achieve 65 mi/h in 170 seconds, taking only 145 seconds. They showed good control linearity and compensation for passenger load under acceleration. The cars generally met the acceleration variation

and jerk rate requirements of $\pm$ 0.6 mi/h/s and 2.0 $mi/h/s^2$, respectively, under acceleration, with the exception of a 2.3 $mi/h/s^2$ jerk rate at the P1 (minimum acceleration) controller position; in this mode the jerk limiting circuitry is inoperative.

The reader should note that the vehicles' braking and propulsion system components were adjusted by the systems' manufacturers, WABCO and General Electric, respectively, prior to the commencement of performance testing. In those instances where the vehicles did not meet the specification criteria it may be possible to make adjustments that will improve the performance to satisfy the specification.

The braking performance of the cars was examined for blended braking in the normal electro-pneumatic (EP) mode of operation, and in a backup mode using straight air pipe pressure (SAP) to sense braking demand. The braking performance was also examined with friction-only and dynamic-only braking, and for the emergency mode initiated by each of the emergency measures available on the cars. Braking test runs were made with initial speeds up to 60 mi/h.

The maximum average blended braking deceleration under EP control satisfied the specification requirement of 2.75 mi/h/s. Under SAP control, the deceleration was 0.25 mi/h/s lower, with a corresponding increase in distance and time required to stop. In the friction-only mode, the system satisfied the specification requirement of 2.75 mi/h/s, from initial speeds up to 35 mi/h. However, from initial speeds of 60 mi/h, the rate was 0.5 mi/h/s low. Rationally, an increase in the response time could be expected for the SAP mode compared to the EP, but deceleration rates should be independant of the mode of operation. The explanation for the decreased deceleration rates in the SAP mode is speculative, but could lie in the production tolerances of the control valves.

In the emergency brake mode, deceleration rates were acceptable at vehicle weights representing seated passenger and standing passenger configurations with values in the range of 3.2-3.7 mi/h/s (with the exception of a trip-cock-initiated emergency at 3.0 mi/h/s). At rush hour passenger load, the car did not meet the specification requirements of a 3.25 mi/h/s emergency braking rate; values obtained ranged from 2.8 to 3.0 mi/h/s. Dynamic braking was effective down to 15 mi/h, except for the rush hour passenger load case where it was marginally worse at 15-18 mi/h; the specification requirement is 15 mi/h.

In the normal operating mode, EP blended braking, the vehicles met the acceleration variation and jerk rate requirements, $\pm$ 0.6 mi/h/s and 2.0 $mi/h/s^2$, respectively. The cars did not meet the jerk rate requirement with friction-only braking (this was not considered to be a normal operating mode).

Friction braking duty cycle and energy consumption runs were carried out using simulated revenue runs representing the MBTA Blue Line and several other revenue profiles representing other transit properties. During the friction brake duty cycle run, the brake shoe temperatures stabilized at 200-210°F. Brake temperatures in service are likely to be higher due to local conditions, such as operation in tunnels with limited air circulation.

Energy consumption for the two-car train operating on a simulation of the MBTA Blue Line varied between 11.82 and 12.20 kWh/mi.

A series of noise tests was conducted to determine the noise levels inside the cars and at the wayside under normal operating conditions. Tests were conducted at various speeds and under acceleration and braking. An interior noise survey was conducted and exterior measurements were taken at a distance of 50 ft from the track centerline.

The vehicles met the only specification criterion for interior noise levels, that the level for a stationary vehicle should not exceed 70 dBA. At speed, the interior noise levels were generally in the 68-72 dBA range, with peaks at grade crossings and switches of 72-74 dBA. Wayside noise levels met the specification requirement of a maximum level of 80 dBA, measured 50 ft from the track at 40 mi/h. Noise levels in excess of 80 dBA were measured above 40 mi/h, with levels in the range 87-90 dBA at 60 mi/h; however, wayside noise levels are considered satisfactory and within specification requirements for operation on the Blue Line where speeds are not expected to exceed 40 mi/h.

Ride quality tests were carried out to determine the ride quality of the vehicles under typical operating conditions. The effects of speed, vehicle acceleration and braking, passenger load, and track type were examined. The vibration induced by the vehicles' undercar equipment was also examined. Ride quality measurements were taken on the carbody floor (at the centerline) for a forward location over the leading truck and for a center location. Vertical, lateral, and longitudinal acceleration data were recorded.

The MBTA Blue Line cars exhibited very low levels of vibration. At constant speed, the highest rms levels (0.055 g) were recorded at 60 mi/h, at seated passenger weight. Under maximum acceleration, rms levels of 0.042 g were recorded in the midcar vertical measurement at standing passenger weight. For deceleration runs, the highest rms level achieved, 0.032 g, occurred under maximum braking conditions at 60 mi/h, again with a standing passenger weight.

Comparing averaged peak levels of acceleration, the highest frequency component at constant speed occurred at 60 mi/h in the midcar vertical measurement (0.025 g at 10 Hz). Under acceleration, the highest frequency component occurred during a P2 controller setting acceleration (0.011 g at 30 Hz). Similarly, the braking runs gave a highest frequency component of 0.014 g at 30 Hz for a stop from 20 mi/h at seated passenger weight.

The highest components in lateral and forward car vertical measurements were typically the 1 to 3 Hz rigid body mode components. They were observed consistently in all ride quality runs.

The vehicle met the only specification requirement for ride quality, that instantaneous acceleration due to component-induced vibration should not exceed 0.04 g.

A test was carried out to determine the braking performance, squeal, and wear characteristics of three experimental brake shoe types. The shoes tested were WABCO type 539, Abex type T-176-4, and Griffin Anchor type. A series of brake applications were made to bring the brakes to a stable operating

temperature and then braking performance runs were made, recording stopping distances and noise levels due to brake squeal. Prior to the start of testing, the brake cylinder pressures were adjusted for each type of shoe to meet the braking performance criteria with the brakes cold. The shoes were weighed at the start and conclusion of the testing for each shoe type to determine wear characteristics.

In comparison with the original equipment brake shoes (WABCO type 392), performance of the experimental shoes was satisfactory at speeds up to 50 mi/h. Above this speed there was a marked deterioration in stopping distance for the WABCO and Abex experimental shoes. The Griffin Anchor shoes had better stopping distance performance than the standard shoes throughout the speed range.

Noise levels due to brake squeal were higher for the blended braking test than for friction-only; all brake squeal occurred at low speeds. The WABCO brake shoes were noisiest, with Griffin next, and Abex quietest. Typical noise levels inside the car at the conductor's seat, with the crew windows open, were 110 dBA, 93 dBA, and 64 dBA, respectively, for new brake shoes.

The brake shoe weight loss measurements were inconclusive as indicators of wear rates, because the test was of short duration.

An energy conservation test phase was conducted in which modifications to the vehicle acceleration and deceleration rates, cutoff speed, and reset speed were evaluated. The cutoff speed is the speed at which power is automatically removed by the vehicle control system; reset speed is the speed at which it is automatically reapplied. Seven control system configurations were evaluated by testing them over a simulation of the Blue Line revenue service run. Energy consumption measurements were restricted to the vehicles' propulsion system and excluded energy consumed by auxiliary systems. Potential energy savings of up to 22% were identified, compared to the energy consumed by the standard configuration, with round trip time penalties of up to 2 minutes for the 10-mile run. The largest savings resulted from a configuration with a cutoff speed of 31 mi/h, a reset speed of 27 mi/h, and average acceleration/deceleration levels of 3.0 mi/h/s.

The Blue Line cars 0608 and 0609 demonstrated above-average reliability, and no major problems were experienced during their stay at TTC. In all, 11,263 miles of running were accumulated on the TTT in support of the test program, and 99% of the scheduled track time was used, demonstrating the reliability of the cars.

The test program was accomplished on schedule with the exception of a 70-day period (before testing began) when production modifications were incorporated in the vehicles. Performance, ride quality, and noise test phases were accomplished in 34 days, the brake shoe evaluation took 44 days, and the energy conservation phase was completed in 30 days.

INTRODUCTION

This report presents the results of a series of engineering tests carried out on the Massachusetts Bay Transportation Authority (MBTA) Rapid Transit Cars from April through October 1979, at the Department of Transportation, Transportation Test Center (TTC), Pueblo, Colorado. The test program was sponsored by the Office of Rail and Construction Technology in the Office of Technology Development and Deployment, Urban Mass Transportation Administration (UMTA), Washington, D.C. The TTC conducted the tests according to established test procedures; additional support and test requirements were supplied by Hawker-Siddeley Canada Ltd. MBTA provided a full-time representative from their engineering consultant, L. T. Klauder and Associates, who furnished technical input for the special engineering brake shoe evaluation and energy consumption tests.

1.0 BACKGROUND

In 1973, specifications for Blue Line and Orange Line cars were released by the MBTA. The original specifications were subsequently rewritten to provide greater similarity between the two car designs and were reissued in 1974. A contract was signed on August 19, 1976, with Hawker-Siddeley Canada Ltd., for production of 70 Blue Line and 120 Orange Line cars. The MBTA, in cooperation with UMTA, requested the Federal Railroad Administration (FRA) to conduct engineering tests on a married pair of newly designed Blue Line vehicles at the TTC.

2.0 TEST PROGRAM SCOPE

The purpose of the tests was to evaluate the MBTA Blue Line vehicles in the areas of performance (propulsion, control, and braking), ride quality, and wayside and onboard noise. Additional test objectives were to conduct tests on experimental brake shoes, and also on energy consumption, in order to optimize energy efficiency and reduce environmental impact on the Blue Line.

The performance, ride quality, and noise engineering tests were carried out to the overall guidelines of the General Vehicle Test Plan (GVTP).

The test results will provide valuable information for (1) determining the specification compliance of the vehicles, (2) establishing operation and maintenance policies, (3) establishing and upgrading vehicle specifications, and (4) future vehicle development efforts.

2.1 THE GENERAL VEHICLE TEST PLAN

The GVTP for Urban Rail Transit Cars, Report No. UMTA-MA-06-0025-74-14, provides a methodology for testing, documenting, and analyzing data in the testing of urban rail transit cars, with the objective of evaluating the total vehicle performance on a standardized basis to provide technical information for:

- Qualitative analysis of comparative vehicle systems,
- Identifying technical areas where research and development (R&D) is desirable,
- Defining system improvement achieved by R&D, and
- Maintaining a data bank for transit properties and vehicle manufacturers who plan and develop new transit systems.

The GVTP details test procedures in eight vehicle test categories. Five of these categories were pertinent to the MBTA test program:

- Performance (propulsion, control, and braking),
- Power consumption,
- Noise,
- Ride quality, and
- Simulated revenue service.

The test procedures detail test variables such as vehicle weight, line voltage, and controller levels. These variables were modified as necessary to suit the individual characteristics of the MBTA car.

2.1.1 Consist

Testing was limited to a two-car married train. The Blue Line cars are normally operated in trains of up to eight cars. Each pair of cars within the train is "married"; i.e., it cannot be operated without a complementary car that is permanently coupled to it, a requirement dictated by undercar equipment allocations.

2.1.2 Controller Level

The master controller had four discrete levels of power application, P1 (minimum) through P4 (maximum), and the vehicle was tested at each of these settings. The master controller also had two indicated brake positions, minimum and full service, with variable positioning between the two, and an emergency position. Brake tests were conducted with the master controller in four positions: minimum, full service, an intermediate position between full service and minimum, and emergency. The intermediate position was defined as 50% of the straight air pipe (SAP) pressure at full service braking (50% = 35 psig).

2.1.3 Friction Brake System

The friction brake system is normally an electro-pneumatic (EP) controlled system actuated by movement of the master controller. If the EP portion fails, the brake system then reverts to a full pneumatic SAP control system. One movement of the master controller actuates either system. To meet a Hawker-Siddeley requirement, all testing was conducted first with EP braking, then repeated with SAP braking.

2.1.4 Input Voltage

The nominal Blue Line voltage is 575 V d.c. at the third rail pickup, but due to TTC rectifier station limitations, the lowest voltage that could be set at TTC was 620 V d.c. Maximum vehicle allowable voltage was 650 V d.c.; these two limitations precluded testing high and low voltage situations. Therefore, the nominal voltage at the TTC was maintained at 620 V d.c. at the third rail pickup. It should be noted that the nominal voltage is set under near "no-load" conditions (i.e., vehicle auxiliaries operating), and that significant voltage drops are experienced under load. These are illustrated in section 6.1, Performance Characteristics, Acceleration.

2.1.5 Vehicle Weight

The vehicles were tested at four weights, simulating varying passenger lading by lead ingots placed on the carbody floor. The four ladings represented empty weight, seated passenger weight, standing passenger weight, and maximum (crush) passenger weight. The nominal and the actual weights used in the test program are listed in table 2-1, Vehicle Weights.

TABLE 2-1. VEHICLE WEIGHTS.

Condition	Weight Code	Nominal Weight (lbs)	Actual Weight (lbs) Car 0608	Car 0609
Empty	AW0	60,160	60,740	61,860
Seated Passengers	AW1	65,160	64,560	64,300
Standing Passengers	AW2	70,160	69,940	69,240
Maximum Passengers	AW3	75,160	74,920	74,450

Note: Actual weight included instrumentation and the data acquisition system, but excluded the average test crew weight of 1,200 lbs, as this was a variable from day to day.

2.2 MBTA TESTS

2.2.1 Standard Tests

The scope of the performance, ride quality, and noise tests resulting from the integration of the GVTP guidelines and the constraints discussed here are detailed in table 2-2, MBTA Standard Tests.

2.2.2 Special Engineering Tests

At the conclusion of the GVTP portion of the program, special engineering tests were defined by MBTA, directed by L.T. Klauder and Associates, and conducted by the TTC:

- A brake shoe test, to evaluate the performance of experimental brake shoes, and

- An energy conservation test, to evaluate possible energy savings obtained by operating with different vehicle control parameters.

In addition, two other vehicle characteristics were subjected to further measurement. First, vibration data for the truck frame and traction motor assembly were collected during the ride quality test runs. These data were used to examine the transfer functions between truck and vehicle body as part of the ride quality test program. Second, potential sources of coupler noise were investigated with closed-circuit television and displacement transducers. The coupler noise tests resulted in a proposed modification to the design clearances of the draw bar pin, which is currently under consideration at MBTA.

TABLE 2-2. MBTA STANDARD TESTS.

GVTP Test Set	Title	Vehicle Weights	Remarks
P-2001-TT	Acceleration	AW0,AW1,AW2,AW3	4 Master Controller Positions
P-3001-TT	Deceleration-Blended Braking	AW0,AW1,AW2,AW3	Repeated for EP and SAP Braking
P-3002-TT	Deceleration-Friction Braking	AW0,AW1,AW2,AW3	Repeated for EP and SAP Braking
P-3003-TT	Deceleration-Dynamic Braking	AW0,AW1,AW2,AW3	
P-3004-TT	Deceleration-Emergency	AW0,AW1,AW2,AW3	
P-4001-TT	Drift Test	AW0,AW1,AW2,	
P-5001-TT	Duty Cycle-Friction Brake	AW2	
PC-5011-TT	Power Consumption	AW2	
R-0010-T	Component-Induced Vibration	AW1	
R-1101-TT	Worst Speeds	AW1,AW2,AW3	
R-2001-TT	Acceleration	AW1,AW2,AW3	
R-3001-TT	Deceleration	AW1,AW2,AW3	
PN-1001-TT	Speed Effect-On Car	AW1,AW2,AW3	
PN-1101-TT	Track Type Effect-On Car	AW1,AW2,AW3	
PN-1301-TT	Interior Survey	AW1,AW2,AW3	
PN-2001-TT	Acceleration-On Car	AW1,AW2,AW3	
PN-3001-TT	Deceleration-On car	AW1,AW2,AW3	
CN-0001-TT	Equipment Noise Survey	AW1	
CN-1001-TT	Speed Effect Wayside	AW1,AW2,AW3	Basic Test without Motor Shrouds Repeated at AW3 with Motor Shrouds

Tests were conducted on three types of experimental brake shoes to evaluate their performance in the areas of:

- Brake fade, as determined by stopping distance,
- Brake noise,
- Thermal characteristics,
- Wear, and
- Effect of vehicle weight on performance.

A series of energy consumption tests were conducted using a test run that simulated the MBTA Blue Line revenue service profile with 22 station stops. Intermediate station stops were of 30 seconds duration and the first/last station stop was 2 minutes. The objectives of the tests were to study the effect of changes in the vehicle propulsion control circuitry to modify the speed/time characteristics, and to determine the effect of those changes on vehicle energy consumption and round trip time when operating on the Blue Line route.

2.3 CHRONOLOGY

A schedule summary for the MBTA test program is illustrated in table 2-3, which compares scheduled activity days with actual days. The actual duration of each phase of the test program matched the predictions closely, with the exception of a 70-day period used by Hawker-Siddeley to modify the cars to a production standard and to make adjustments.

TABLE 2-3. SCHEDULE SUMMARY.

Activity	Scheduled Days	Actual Days
Unload Cars	2	2
Function Test and Instrumentation	14	14
Car Setup and Modification	0	70
Test Operations Spec. Compliance General Vehicle	35	34
Special Engineering Brake Evaluation	48	44
Energy Consumption	28	30

3.0 DESCRIPTION OF VEHICLE

The following paragraphs describe the general features of the MBTA Blue Line cars in terms of required performance, dimensions, passenger load, and vehicle construction. The salient features of the carbody, trucks and suspension, propulsion and control system, traction motors, and braking system are identified.

3.1 GENERAL VEHICLE DESIGN PARAMETERS

The two test vehicles, serial numbers 0608 and 0609, were built by Hawker-Siddeley Canada Ltd., to meet MBTA specification "Equipment Engineering No. 590, No. 4 East Boston Rapid Transit Cars," MBTA, August 1976. A photograph of the test vehicles is presented as figure 3-1, and the general vehicle design features are described in table 3-1.

TABLE 3-1. VEHICLE DESCRIPTION.

Length	48 ft 10 in
Width	9 ft 3 in
Height	8 ft 6 in
Empty Weight	60,160 lbs
Seated Passenger Load	65,160 lbs
Standing Passenger Load	70,160 lbs
Crush Passenger Load	75,160 lbs
Maximum Speed	65 mi/h
Maximum Acceleration	2.5 mi/h/s
Full Service Braking	2.75 mi/h/s
Emergency Braking	3.25 mi/h/s

3.2 CARBODY

The carbody is a steel welded structure of high tensile, low alloy steel; it includes the entire underframe, body structure, and side, end, and roof sheets. Because of floor height constraints, the main floor supports are I-beams that run fore and aft instead of the traditional full depth floor beams

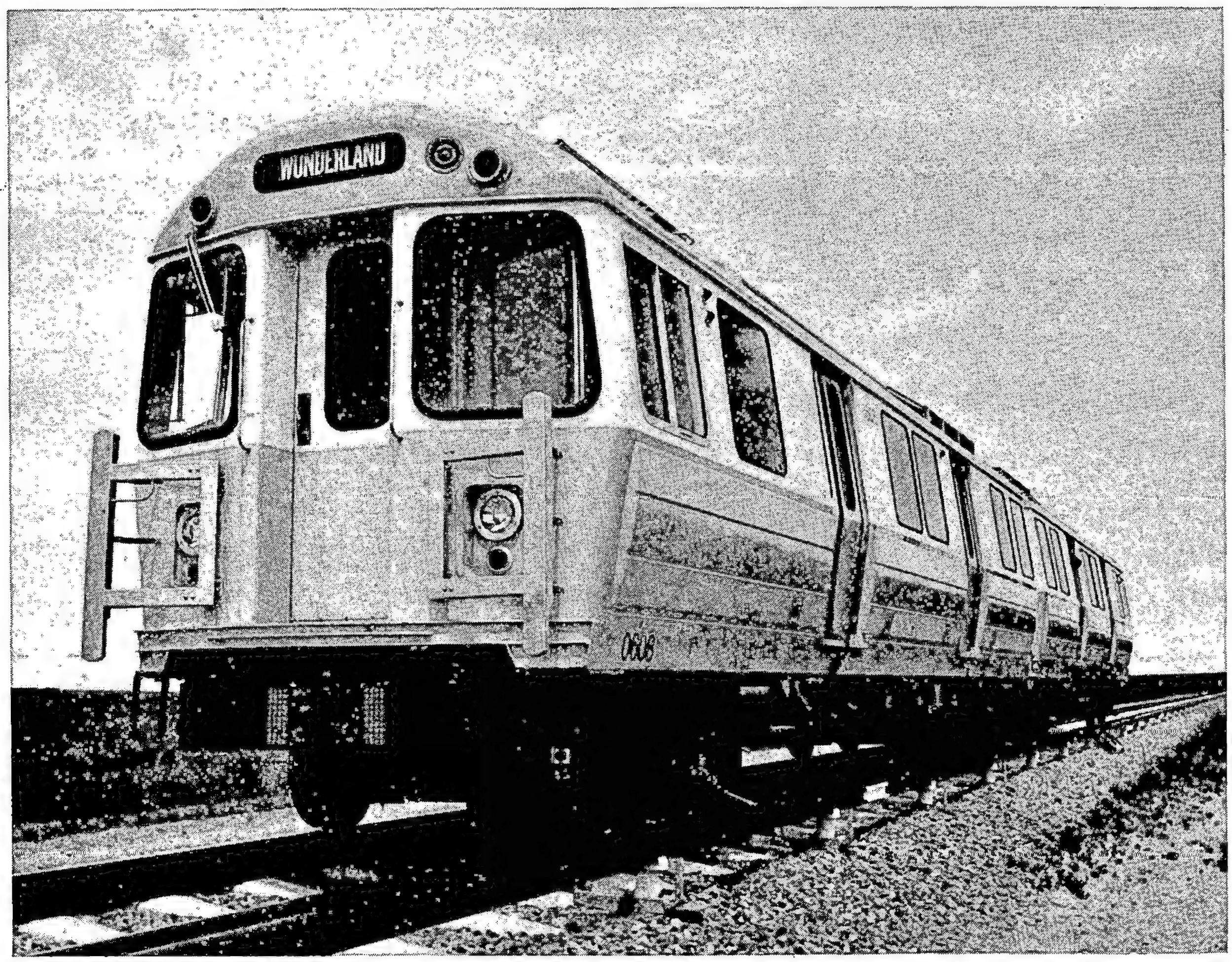


FIGURE 3-1. MBTA BLUE LINE VEHICLES (MARRIED PAIR).

that run from side to side. Thus, two center sill I-beams are located 40" apart, and the floor panels are supported on the center sill I-beams and side sills. The end frames, incorporating the bolsters, draft sills, and anticlimbers, are welded to the side sills.

3.3 TRUCKS AND SUSPENSION

Each car has two 4-wheel, swivel-type inside journal trucks with two traction motors mounted on each truck, one motor geared to each axle. Two 28" wheels are rigidly attached to each axle to form a wheelset. The truck frame is of cast steel construction; the frame is cast in sections that are then welded together in a unique cast-weld process. Primary suspension is provided by elastomeric chevron springs mounted between the axle journals and the truck side frames; secondary suspension consists of two air springs per truck, mounted between the bolster and the car body underframe. The bolster-to-carbody longitudinal relationship is maintained by two resiliently mounted radius rods connecting the bolster and underframe. Passenger load is sensed at each truck, and air spring pressure is varied accordingly to maintain a constant floor height of 41.5" above the rail.

3.4 PROPULSION AND CONTROL SYSTEM

The propulsion and control system is a conventional cam-controller type. An electric motor-operated power/brake cam controller responds to signals from the master controller, and selects one of four basic types of traction motor current control. The four control configurations are two series connections, series/parallel connection of pairs of traction motors, and one stage of field weakening. The purpose of these four controller positions, known as P1 through P4, is described briefly in table 3-2. Logic circuits in the propulsion and control system compensate for vehicle weight to provide constant acceleration and deceleration levels regardless of passenger load. These circuits also provide jerk (rate of change of acceleration) limit protection.

TABLE 3-2. CONTROLLER POWER POSITIONS.

Controller Position	Purpose	Maximum Speed (mi/h)
P-1	Minimum Acceleration - Switching	10
P-2	Intermediate Acceleration - Operations	25
P-3	Maximum Acceleration - Operations	45
P-4	Maximum Acceleration (minimum field) - Operations	65

3.5 TRACTION MOTORS AND TRANSMISSIONS

Two 4-pole d.c., series-wound traction motors are suspended from rubber cushioned hangers on each truck. Each motor operates on 300 V d.c., and each pair of motors is connected in series. They are resiliently mounted to two parallel-type reduction gear box units with a 6.13:1 overall reduction ratio. Misalinement between motor and gear box is accommodated by a gear-type coupling.

3.6 BRAKING SYSTEM

Under normal operation, the major braking effort is provided by the dynamic braking capability of the vehicle propulsion system, with backup braking effort provided by the friction brake system. In practice, the friction brakes supplement during the transition from power mode to brake mode, and provide all braking when dynamic braking ceases at low speeds. If the dynamic braking system should fail, full service braking would be provided by the friction brake system.

The term "blended braking" is commonly used to define continuous blending of dynamic and friction brake effort to achieve a constant deceleration rate. In the case of the MBTA car, the normal service braking could be more accurately described as "switched" braking, since the propulsion system senses dynamic brake armature current and switches from dynamic to friction braking below 30 A (or similarly from friction to dynamic above 30 A). The only true blending occurs at the transition from one braking mode to the other. To maintain a consistency with commonly used terminology, the term "blended braking" is used in this report to denote the normal braking mode of the MBTA car.

Braking is provided by an EP system that activates dynamic motor braking and a tread brake unit on each wheel. If the electronic control system fails, the brake system reverts to a SAP system. In this case, the dynamic braking signal is sensed by a transducer in the trainline air pipe. Emergency braking is provided by the friction brake system only, and is air-initiated from the trainline brake pipe.

4.0 DESCRIPTION OF FACILITIES

The following paragraphs describe the six sections of the test track, including details of construction, profile, and perturbation amplitude and wave form. A brief description of the climatic conditions prevalent at the TTC is also given.

4.1 TEST TRACK

The tests were conducted on the Transit Test Track (TTT), a 9.1-mi oval incorporating six typical types of transit track construction. The TTT includes a perturbed section, typical grade crossings and switches, and a 4,000-ft level tangent section that is used for all performance testing and for instrumentation calibration prior to each day's testing.

Track orientation and plan are shown in figure 4-1, and the track profile is shown in figure 4-2. Table 4-1 shows the characteristics of each of the six track sections. The perturbed section of the TTT track is located between stations 11.8 and 14.0. The perturbations were made only to the outer rail in profile and alinement; wavelength varied between 14 and 56 ft. Table 4-2 details the amplitude and waveforms of the perturbations. The level tangent section of track between stations 30.0 and 34.0 was used for all brake, acceleration, and tractive resistance tests.

The track is designed for sustained 80 mi/h vehicle operation with the exception of the perturbed track section, which is subject to a speed limit based on ride quality test requirements and safety considerations. For this program, the test speed limit for the perturbed section was 65 mi/h.

The third rail was constructed to New York City Transit Authority (NYCTA) specifications. A special third rail shoe (supplied by Ohio Brass) was used to make the MBTA Blue Line vehicles compatible with the TTT third rail configuration.

Power was supplied by a rectifier station purchased from the Chicago Transit Authority (CTA). Nominal no-load line voltage at the third rail shoe was 620 V d.c., with a current limit of 7,500 A for two hours. The rectifier station no-load line voltage can be preset from 620-780 V d.c.

4.2 CLIMATIC CONDITIONS

The TTC is located on semiarid rangeland, subject to large daily temperature variations, bright sunlight, and low humidity. Average daily temperatures range between a minimum of 15°F in January and a maximum of 92°F in July. The lowest temperature on record is -31°F and the highest is 105°F. Freezing temperatures occur during 152 days of the year. Annual precipitation averages 12". The sun shines during about 73% of the daylight hours. At ground level, there is typically 25 to 75% more solar radiant energy than along the northeast coastal regions of the United States.

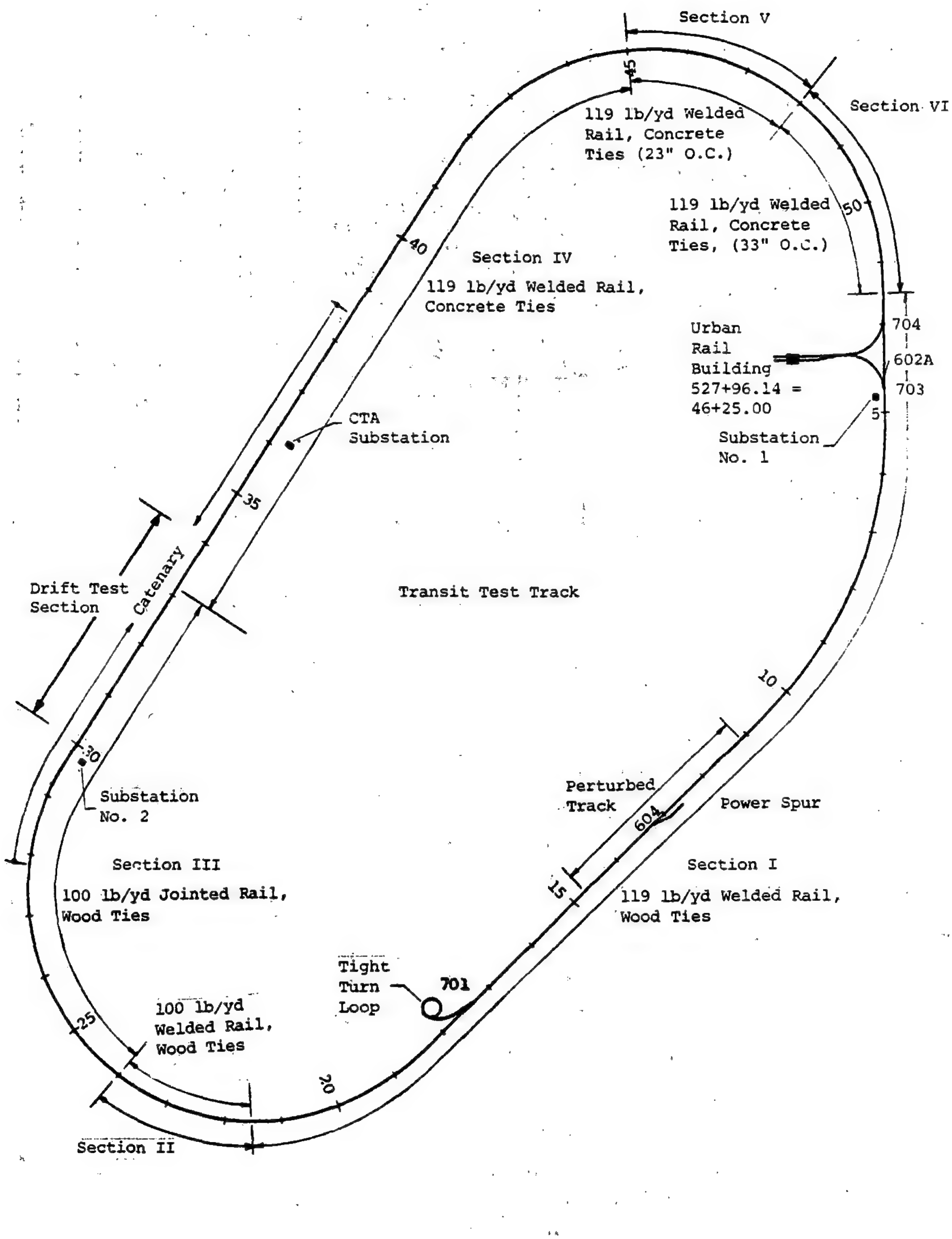
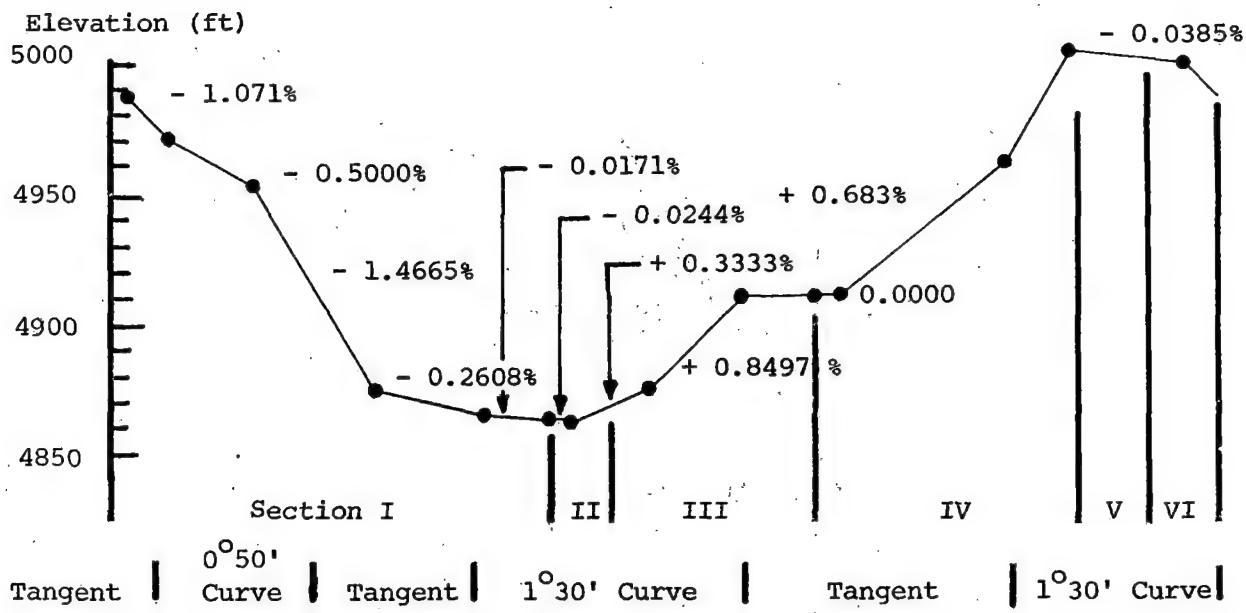


FIGURE 4-1. TRANSIT TEST TRACK.



NOTES

Track Curvature:

Sta.	to	Sta.	Degree of Curve
55.3		10.3	$0^{\circ}50'$
18.9		29.4	$1^{\circ}30'$
41.8		50.8	$1^{\circ}30'$

Curve Superelevation:

$1^{\circ}30'$ curves are superelevated a maximum of 4.5". The maximum superelevation on the $0^{\circ}50'$ curve is 2".

Elevation:

Minimum - 4,863 ft at Sta. 22.0.
Maximum - 5,003 ft at Sta. 46.0.

FIGURE 4-2. TRANSIT TEST TRACK PROFILE SHOWING GRADES.

TABLE 4-1. TTT CONSTRUCTION DETAILS.

Section	Location (Sta to Sta)	Alinement	Trackage	Fastener	Rail
I	51.0 - 17.4	Tangent and 0° 50' curve	Wooden ties 24" on center	Spike	119 lb/yd Welded
	17.4 - 21.5	1° 30' curve	Wooden ties 23" on center		
II	21.5 - 24.0	1° 30' curve	Wooden ties 23" on center	Spike	100 lb/yd Welded
III	24.0 - 29.0	1° 30' curve	Wooden ties 23" on center	Spike	100 lb/yd Jointed
	29.0 - 33.0	Tangent	Wooden ties 24" on center		
IV	33.0 - 40.5	Tangent	Concrete ties 30" on center	Spring Clip	119 lb/yd Welded
	40.5 - 44.0	1° 30'	Concrete ties 27" on center		
V	44.0 - 47.0	1° 30'	Concrete ties 23" on center	Spring Clip	119 lb/yd Welded
VI	47.0 - 51.0	1° 30'	Concrete ties 33" on center	Spring Clip	119 lb/yd Welded

TABLE 4-2. AMPLITUDE AND WAVEFORMS OF TTT PERTURBATIONS, DESIGN SPECIFICATIONS.

Profile					Alinement		
Sta 11.8	Sta 12.0	Sta 12.2	Sta 12.4	Sta 12.6	Sta 13.6	Sta 13.8	Sta 14.0
1.5"	0.38"	0.38"	0.75"	1.5"	0.75"	0.38"	0.75"
1.48" ± 1 tie	0.30" ± 1 tie	0.36" ± 1 tie	0.71" ± 1 tie	1.43" ± 1 tie	0.74" ± 1 tie	0.30" ± 1 tie	0.71" ± 1 tie
1.42" ± 2 ties	0.15" ± 2 ties	0.30" ± 2 ties	0.61" ± 2 ties	1.22" ± 2 ties	0.71" ± 2 ties	0.15" ± 2 ties	0.61" ± 2 ties
1.34" ± 3 ties	0.02" ± 3 ties	0.23" ± 3 ties	0.46" ± 3 ties	0.92" ± 3 ties	0.67" ± 3 ties	0.02" ± 3 ties	0.46" ± 3 ties
1.22" ± 4 ties	0" ± 4 ties	0.15" ± 4 ties	0.29" ± 4 ties	0.58" ± 4 ties	0.61" ± 4 ties	0" ± 4 ties	0.29" ± 4 ties
1.70" ± 5 ties		0.07" ± 5 ties	0.14" ± 5 ties	0.28" ± 5 ties	0.54" ± 5 ties		0.14" ± 5 ties
0.92" ± 6 ties		0.02" ± 6 ties	0.04" ± 6 ties	0.07" ± 6 ties	0.46" ± 6 ties		0.04" ± 6 ties
0.75" ± 7 ties		0" ± 7 ties	0" ± 7 ties	0" ± 7 ties	0.38" ± 7 ties		0" ± 7 ties
0.58" ± 8 ties					0.29" ± 8 ties		
0.42" ± 9 ties					0.21" ± 9 ties		
0.28" ± 10 ties					0.14" ± 10 ties		
0.16" ± 11 ties					0.08" ± 11 ties		
0.07" ± 12 ties					0.04" ± 12 ties		
0.02" ± 13 ties					0.01" ± 13 ties		
0" ± 14 ties					0" ± 14 ties		
Wave Length 56'	14'	28'	28'	28'	56'	14'	28'

Notes: 1. Only outer rail is perturbed.
2. Alinement accomplished by perturbing rail towards outside of oval.
3. Perturbations are symmetrical around station number; distance from station number is indicated in number of ties.

In general, the dry and sandy conditions with minimal industrial pollution result in high wheel rail adhesion. The elevation of the site (4,950 ft) gives a lower air density than is usual at most transit properties. Average barometric pressure is 25.2" of mercury.

5.0 INSTRUMENTATION, DATA ACQUISITION, AND DATA PROCESSING

A detailed discussion of the data acquisition process, a description of the instrumentation used, and the data processing methodology and equipment is included in appendix A. Pertinent aspects of data acquisition, instrumentation, and data processing for each test are included in the following part, Results and Discussion, to provide a detailed supplement to the abstracts in the appendix.

Introduction

RESULTS AND DISCUSSION

6.0 PERFORMANCE CHARACTERISTICS

The purpose of the performance tests was to determine the performance capabilities and operational characteristics of the Blue Line transit vehicles. Performance was evaluated in terms of acceleration and deceleration levels, traction resistance, power consumption, and friction brake thermal characteristics.

The philosophy of the TTC tests was to characterize the vehicles' performance in a configuration defined by the MBTA and the manufacturers. The vehicles' propulsion and braking systems were adjusted prior to the start of performance testing by the respective manufacturers, General Electric and WABCO, to comply with the production configuration current at the time. In some cases, notably acceleration performance, this adjustment resulted in acceleration levels that fell marginally below the vehicle specification requirement. It is conceivable that the vehicles could have been adjusted to meet these requirements more precisely, or in the case of a more serious deficiency, modified components could have been substituted. The TTC had no control over such eventualities, and therefore, allowed the manufacturers to establish the vehicle configuration to their own satisfaction before the tests and now reports on the resulting performance.

Upon completion of the tests, the cars were returned to Hawker-Siddeley for modification. Specification requirements for vehicle performance quoted in this report should, therefore, be used as a guideline for the performance required of the cars, and not as an indication that the cars could not comply with the specification.

6.1 ACCELERATION

6.1.1 Test Objective

To determine overall acceleration characteristics of the test vehicles as affected by controller input level, car weight, and car direction, and to compare the values obtained with the specification requirement. These characteristics were measured on level tangent track. The specification requirements are:

Controller Position	Purpose and Motor Control Mode	Maximum Speed (mi/h)	Minimum Acceleration Level (mi/h/s)
P-1	Minimum Acceleration (Switching, Series)	10	- -
P-2	Intermediate Acceleration (Full Field, Series)	20	- -
P-3	Maximum Acceleration (Full Field, Series-Parallel)	45	2.5*
P-4	Maximum Acceleration (Minimum Field, Series-Parallel)	65*	2.5*

* Constant acceleration must be maintained up to approximately 20 mi/h with a rush hour passenger load (AW3 weight).

The specification requires that:

- The vehicle must obtain 40 mi/h with an AW3 weight load in not more than 25 seconds, and obtain 65 mi/h with an AW3 load in not more than 170 seconds,
- Variation of acceleration rate must be less than 0.6 mi/h/s, and
- Rate of change of acceleration (jerk rate) must be a maximum of 2.0 $mi/h/s^2$.

6.1.2 Test Method

The level tangent section of the TTT between stations 30.0 and 34.0 was used for all acceleration runs (figure 4-1). The test vehicles were accelerated from a standing start for the following variables:

Variable	Test Conditions
Controller Input	P1 through P4
Car Weight	AW1 AW2 AW3
Car Direction	Forward Reverse

Acceleration characteristics were not tested with variable voltage or with variable consist length.

Data were recorded on analog tape, digitized at a rate of 32 samples per second, with values listed every eighth sample. The longitudinal accelerometer output was low pass filtered at 2.5 Hz before recording. In order to present overlay graphs of acceleration and braking characteristics that indicated mean levels (rather than transient fluctuations), longitudinal accelerometer data were further smoothed numerically, using a moving average smoothing technique over 12 samples. Figure 6-1 shows the effect of the numerical smoothing, in this case on a deceleration trace. All performance test results discussed in the acceleration and braking sections (sections 6.1 and 6.2) are derived from numerically smoothed data. Distance was calculated from the speed and time data by integration.

6.1.3 Test Results

a. Controller Position. The effect of the four controller positions on the acceleration level is shown for 10 mi/h and vehicle weights AW1, AW2, and AW3 in figure 6-2. The plot shows the overall linearity of the controller system up to approximately 2.4 mi/h/s, with a marked drop in slope to the 2.5 mi/h/s level, and that the vehicle has good compensation for passenger weight at 10 mi/h.

The speed/acceleration, time/speed, and time/distance relationships for each of the four controller positions at AW1 weight are shown in figure 6-3. The characteristics for AW2 and AW3 weights are shown in figures 6-4 and 6-5, respectively. Vehicle performance was limited to 60 mi/h since there was insufficient level tangent track on which to reach the higher speeds.

The characteristics comply with the specification to produce constant average maximum acceleration up to approximately 20 mi/h. In addition, the specification called for the ability to reach 40 mi/h with an AW3 load in not more than 25 seconds; the married pair took slightly more time, 26.3 seconds. However, it reached 65 mi/h at AW3 weight in approximately 145 seconds, well under the specification requirement of 170 seconds. Although acceleration rates peaked in excess of the specified 2.5 mi/h/s, the average maximum acceleration of 2.4 mi/h/s fell marginally below this specification requirement for all vehicle weights.

b. Line Voltage. Because of d.c. voltage supply constraints, all performance testing was conducted at a nominal line voltage of 620 V d.c. at the third rail pickup. The soft characteristic of the supply system, however, caused the voltage to fall under load as illustrated in figure 6-6. This shows the drop in line voltage that occurred in an acceleration run at P4 control setting to 60 mi/h, where the line voltage fell by 28%.

c. Car Weight. In figure 6-7, the speed/acceleration, time/speed, and time/distance relationships at P4 are shown overlaid for each vehicle weight (AW1, AW2, and AW3). The vehicle met the specification requirement to maintain constant acceleration rates independent of car loading.

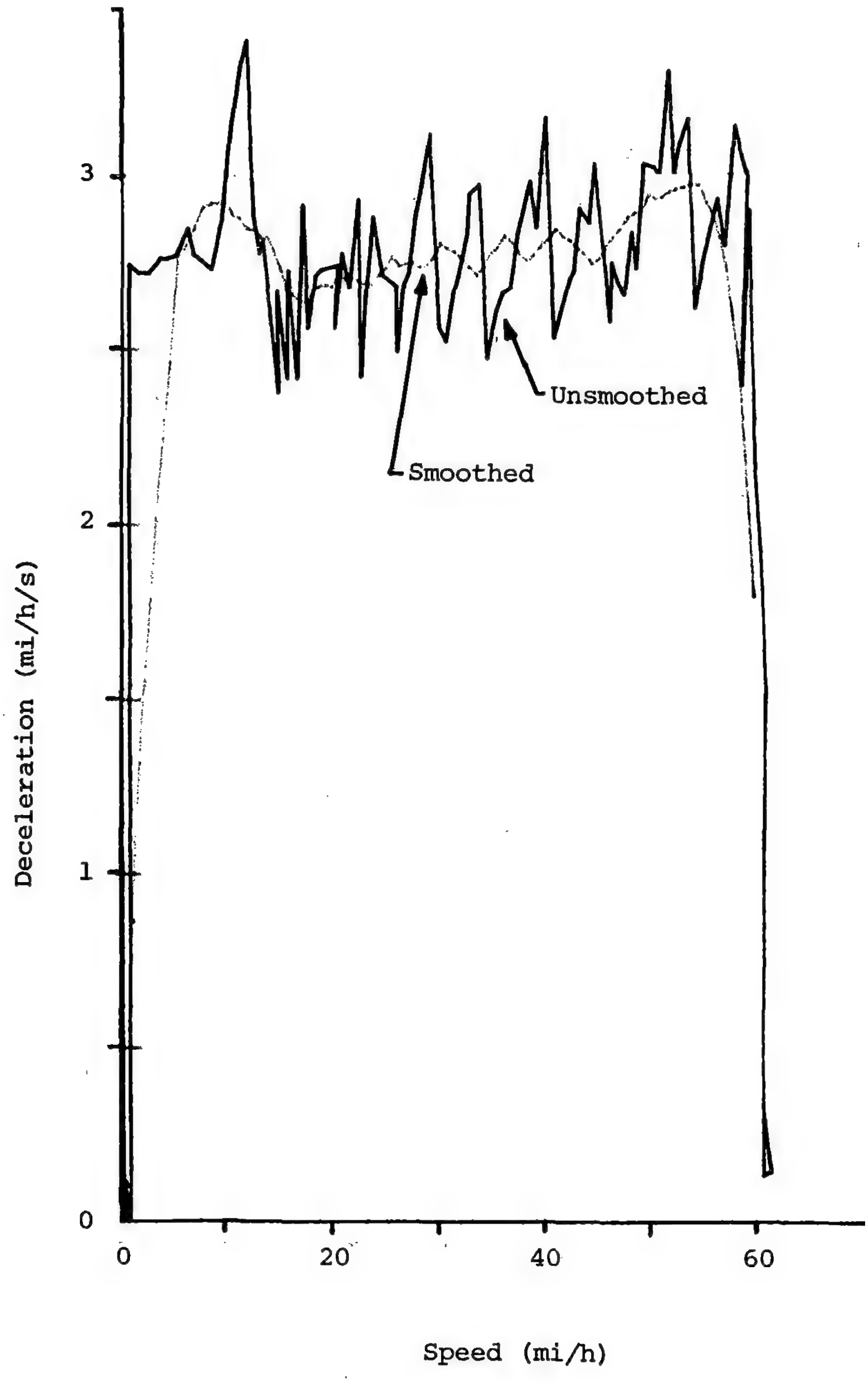


FIGURE 6-1. EFFECT OF NUMERICAL SMOOTHING.

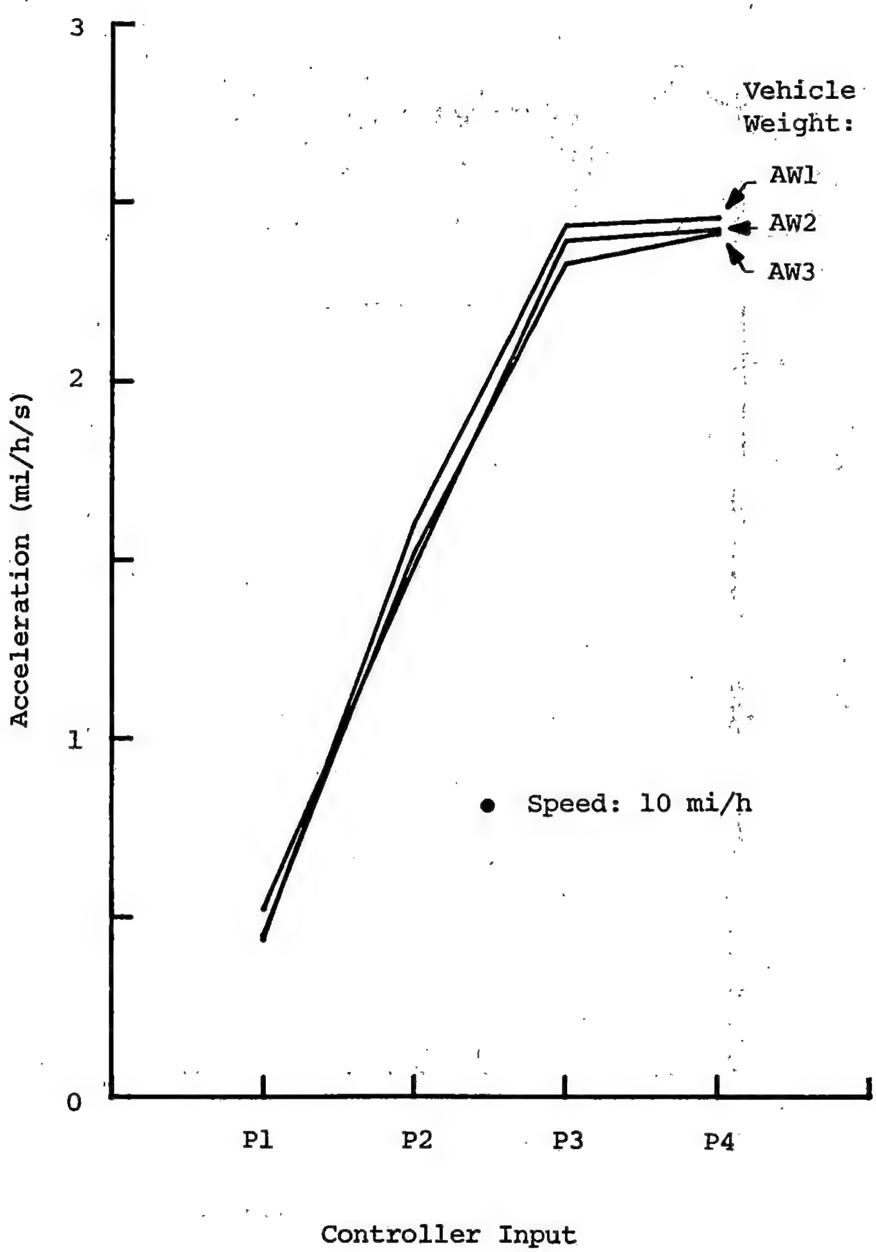


FIGURE 6-2. CONTROLLER LINEARITY AT 10 MI/H.

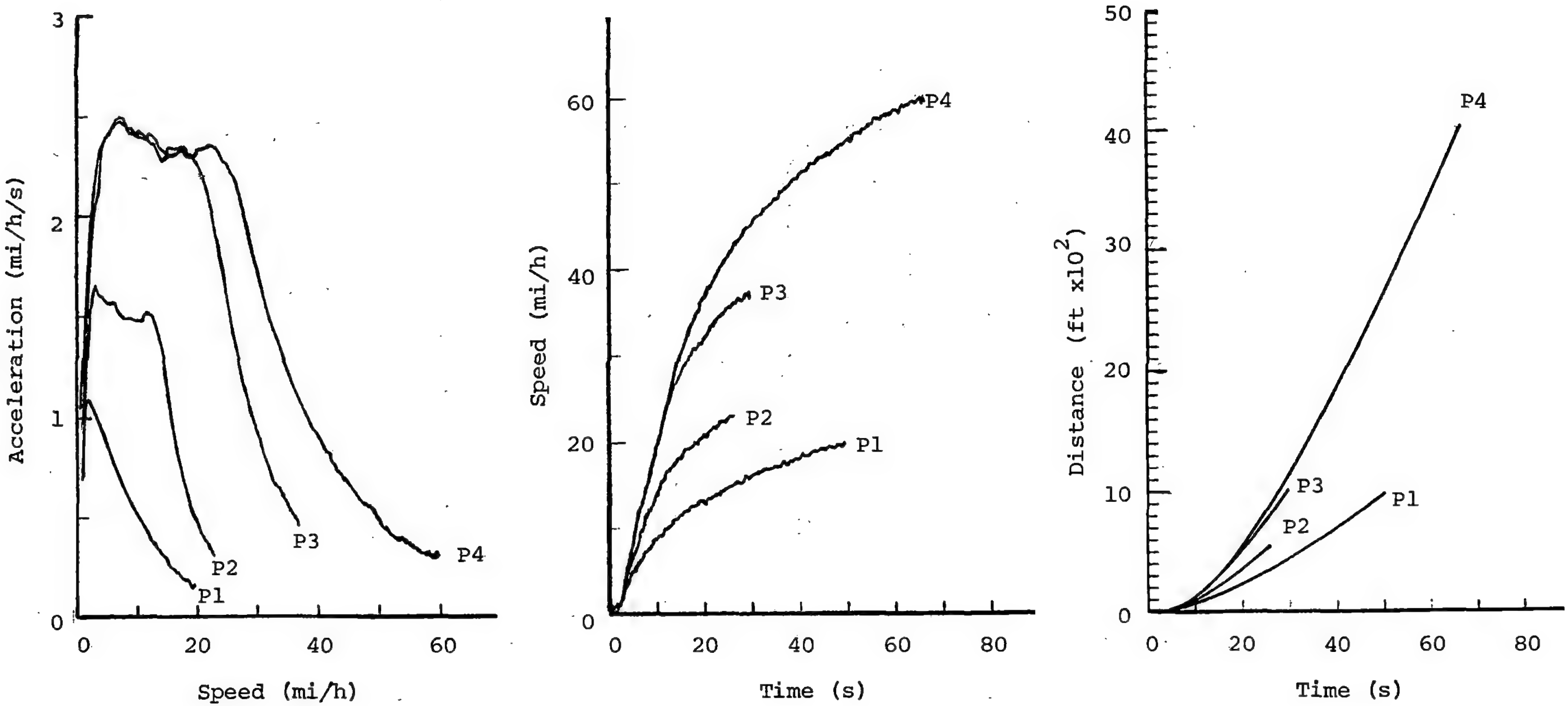


FIGURE 6-3. ACCELERATION PERFORMANCE CHARACTERISTICS AT AW1 WEIGHT.

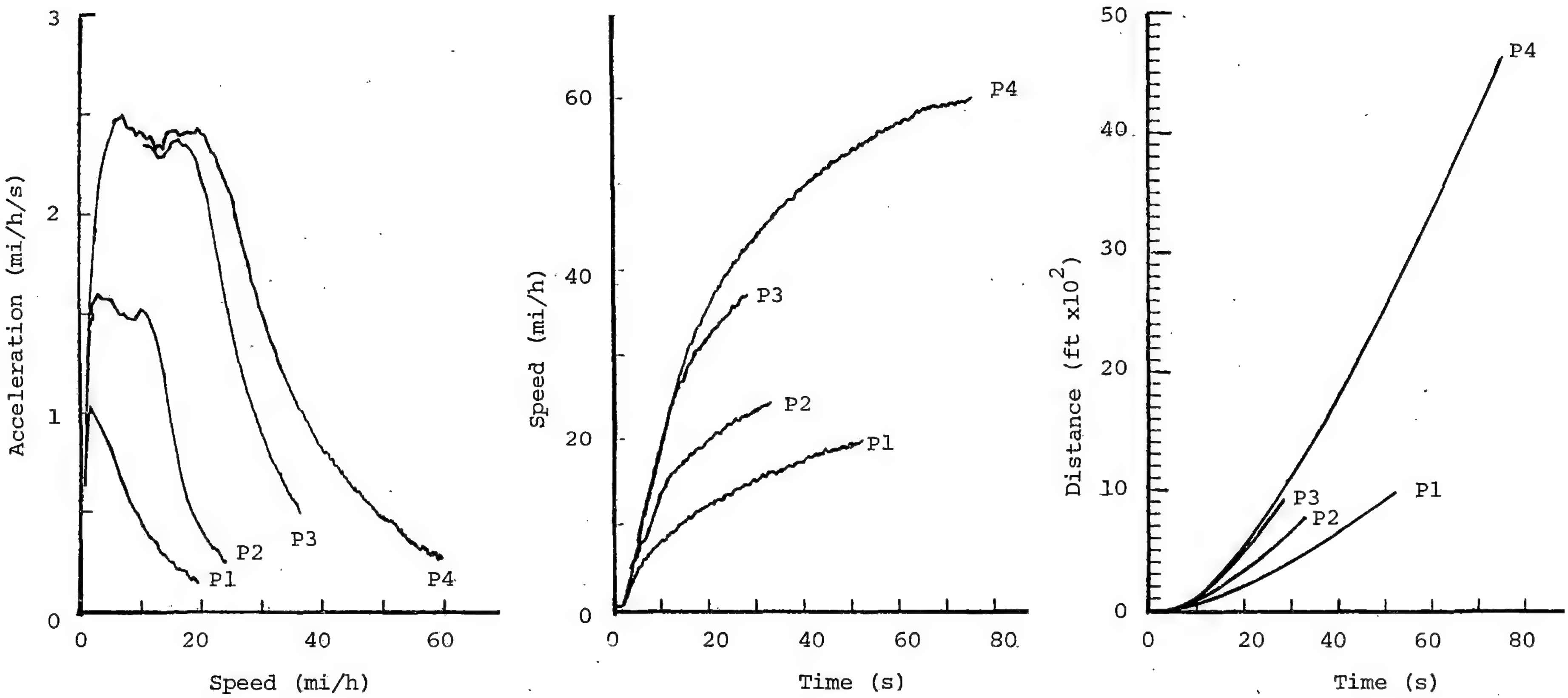


FIGURE 6-4. ACCELERATION PERFORMANCE CHARACTERISTICS AT AW2 WEIGHT.

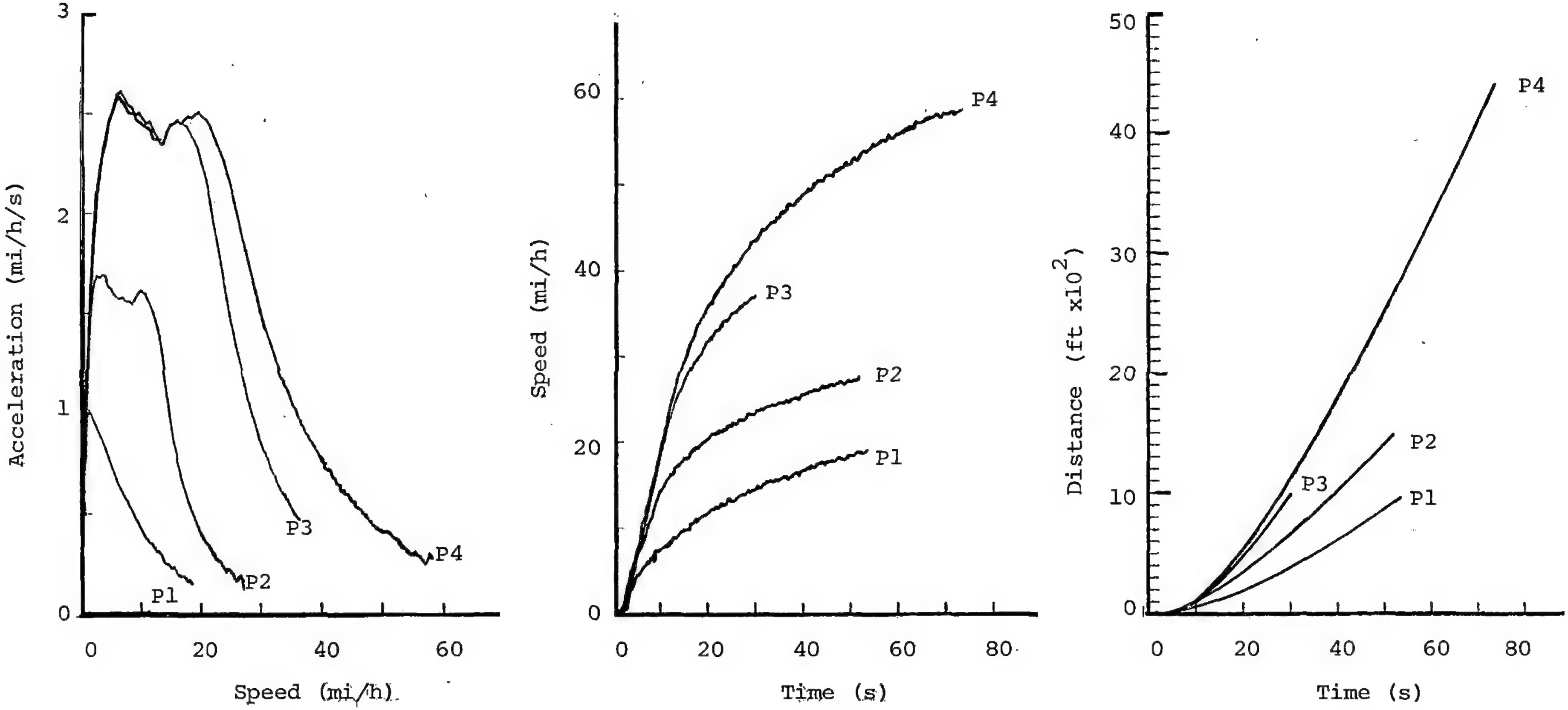


FIGURE 6-5. ACCELERATION PERFORMANCE CHARACTERISTICS AT AW3 WEIGHT.

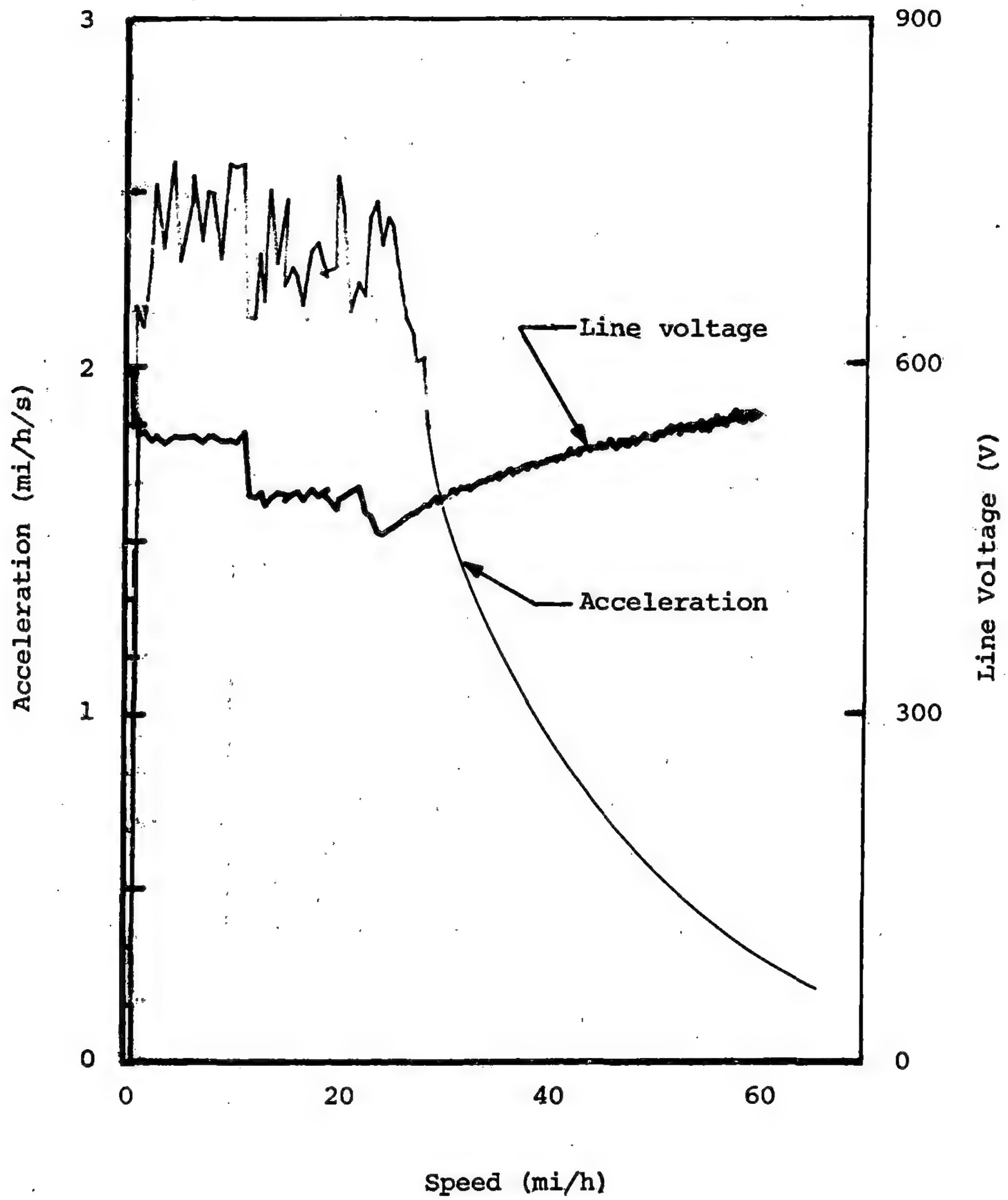


FIGURE 6-6. DROP IN LINE VOLTAGE DURING ACCELERATION.

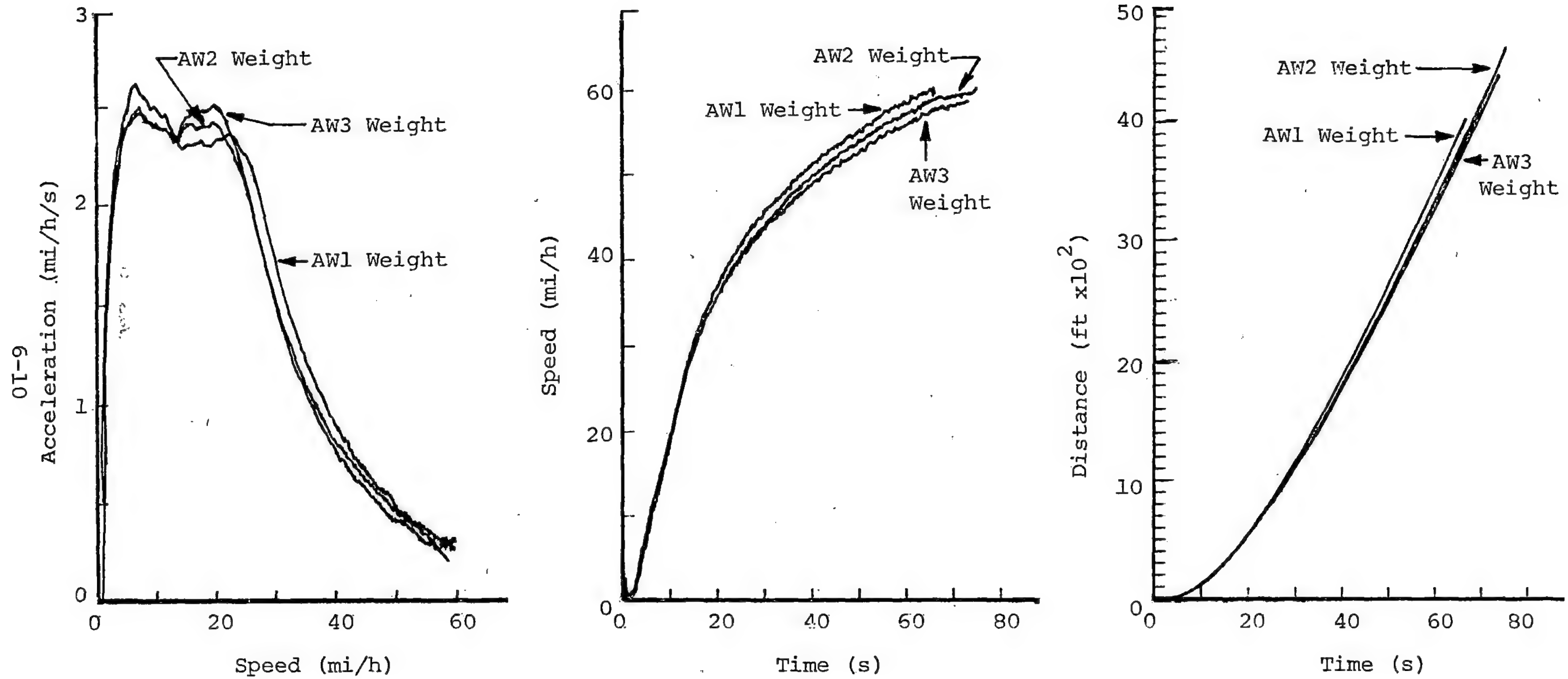


FIGURE 6-7. ACCELERATION PERFORMANCE CHARACTERISTICS FOR CONTROLLER POSITION P4.

d. Direction. The married pair had very similar performance in either direction. Figure 6-8 shows the smoothed curves for speed/acceleration in the clockwise (CW) and counterclockwise (CCW) directions. In this case, acceleration at P4 to 60 mi/h was chosen to illustrate the characteristic; it shows direction to be of no significance to acceleration performance.

e. Jerk Rate. The vehicle specification requires a maximum jerk rate of 2.0 $mi/h/s^2$. Jerk rates as high as 2.3 $mi/h/s^2$ were recorded at AW1 weight in P1 acceleration, although for all other cases the vehicle met the specification requirement. In this acceleration mode, the jerk rate is not controllable within the constraints of the specified propulsion equipment. Jerk rate is normally controlled by the rate of cam controller advance, but in P1, the cam controller is not called into play. The propulsion current is maintained by the staging of large contactors which cut out fixed resistance values. A discussion of the jerk rate calculation is given in the summary of deceleration performance, section 6.2.3.i.

f. Summary. Acceleration performance is summarized in table 6-1.

6.2 DECELERATION

6.2.1 Test Objective

To determine the overall deceleration characteristics for the different brake modes as affected by controller position, car weight, and car direction, and to compare actual performance with the following vehicle specification requirements for braking:

- The maximum average braking rate shall be 2.75 mi/h/s,
- The braking rate shall be independent of car weight up to 15,400 lbs passenger load (AW3),
- Dynamic brakes shall be fully effective down to 15 mi/h,
- Friction brakes shall be capable of maintaining the maximum deceleration rate (i.e., 2.75 mi/h/s) at AW3,
- Emergency brake rate shall be 3.25 mi/h/s,
- Maximum rate of change of deceleration shall be 2.0 $mi/h/s^2$, and
- Maximum variation of deceleration rate shall be 0.6 mi/h/s.

6.2.2 Test Method

The TTT section between stations 30.0 and 34.0 (figure 4-1) was used for deceleration tests. The test vehicle was decelerated under the following variables:

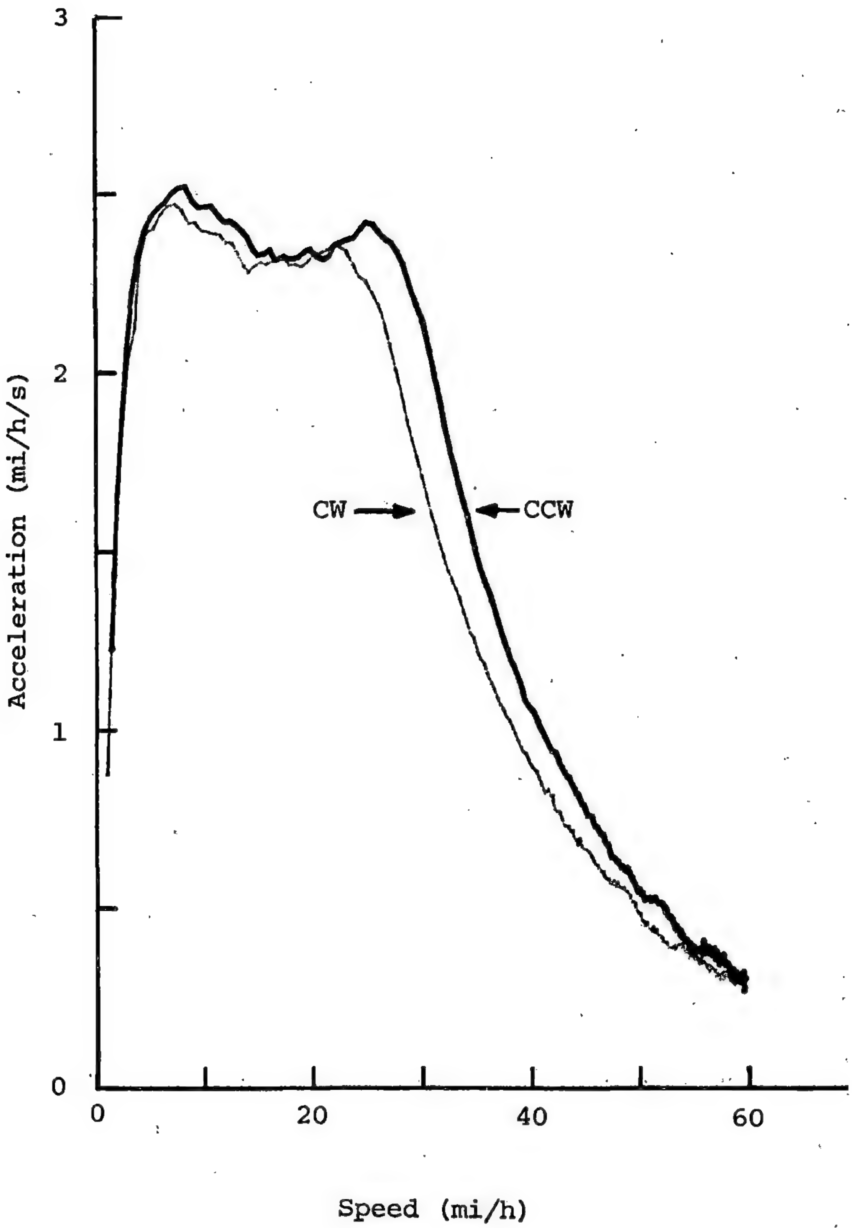


FIGURE 6-8. ACCELERATION PERFORMANCE CHARACTERISTICS, CW AND CCW DIRECTIONS.

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TABLE 6-1. COMPARISON OF ACCELERATION PERFORMANCE AND SPECIFICATION REQUIREMENTS.

Controller Position	ACCELERATION PERFORMANCE (AW1 WEIGHT)			ACCELERATION PERFORMANCE (AW3 WEIGHT)			SPECIFICATION REQUIREMENT (AW3 WEIGHT)		
	Accel. (mi/h/s)	Accel. Variation (mi/h/s)	Jerk Rate ($mi/h/s^2$)	Accel. (mi/h/s)	Accel. Variation (mi/h/s)	Jerk Rate ($mi/h/s^2$)	Minimum Accel. (mi/h/s)	Maximum Accel. Variation (mi/h/s)	Maximum Jerk Rate ($mi/h/s^2$)
P1	0.4	1.4	2.3	0.4	1.2	1.6	-	$\pm$ 0.6	2.0
P2	1.6	+0.4 -0.2	2.0	1.6	+0.6 -0.2	1.8	-	$\pm$ 0.6	2.0
P3	2.4	+0.3 -0.4	2.0	2.6	+0.4 -0.8	1.4	2.5	$\pm$ 0.6	2.0
P4	2.4	+0.2 -0.6	2.0	2.5	+0.2 -0.5	1.4	2.5	$\pm$ 0.6	2.0
Time to 40 mi/h				26.3 seconds			25 seconds		
Time to 65 mi/h				145 seconds			170 seconds		
Constant Maximum Average Acceleration				to 22-25 mi/h			to 20 mi/h		

Variable	Test Conditions
Controller Input	Maximum Brake 50% Brake Minimum Brake
Car Weight	AW1 AW2 AW3
Car Direction	Forward Reverse

The data collection and processing techniques used were identical to those described in 6.1.2.

6.2.3 Test Results

a. Controller Position. In the braking mode, the master controller was continuously variable between minimum and full service braking, with an additional position for emergency braking. For the purposes of the test program, a "50%" service brake position was selected. This was defined by setting a value (35 psig) midpoint between the minimum and maximum braking values of SAP pressure.

Figure 6-9 illustrates the effect of controller level on blended braking deceleration at vehicle weights AW1, AW2, and AW3, from an initial speed of 20 mi/h. The controller input/deceleration relationship is linear throughout the levels of braking and is only slightly affected by vehicle weight.

b. Direction. It was found that performance of the two-car consist was similar in both directions of travel. Figure 6-10 shows typical speed/deceleration characteristics for forward and reverse directions. Because of nearly identical deceleration performance in the forward and reverse modes, the majority of reverse runs were not analyzed.

c. Braking Mode. In the blended brake EP mode, dynamic braking provided deceleration to the speed where friction brakes took over. Figure 6-11 details the control characteristics of speed/deceleration for each control setting (maximum, 50%, and minimum) from 60 mi/h at AW1, AW2, and AW3 weights. Each curve has been smoothed. Figure 6-12 shows the relationship between initial speed/stopping distance and initial speed/time taken to stop for the three control positions at AW2 weight.

The data show that the vehicle meets the specification requirements for full service braking rate (2.75 mi/h/s) throughout its passenger load range in the EP braking mode. Jerk rates and deceleration variations are defined later in this discussion.

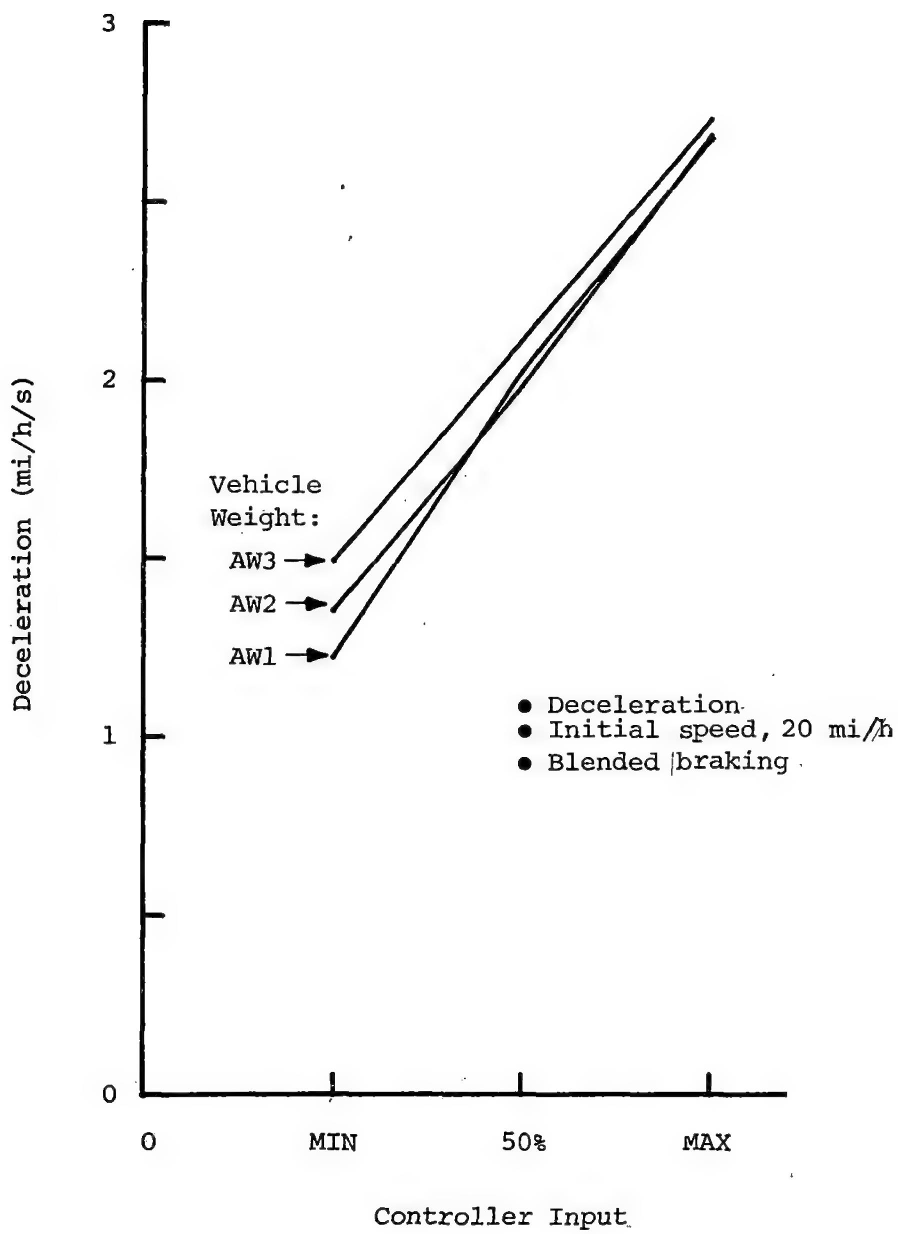

FIGURE 6-9. CONTROLLER LINEARITY AT 20 MI/H, FULL SERVICE BRAKING.

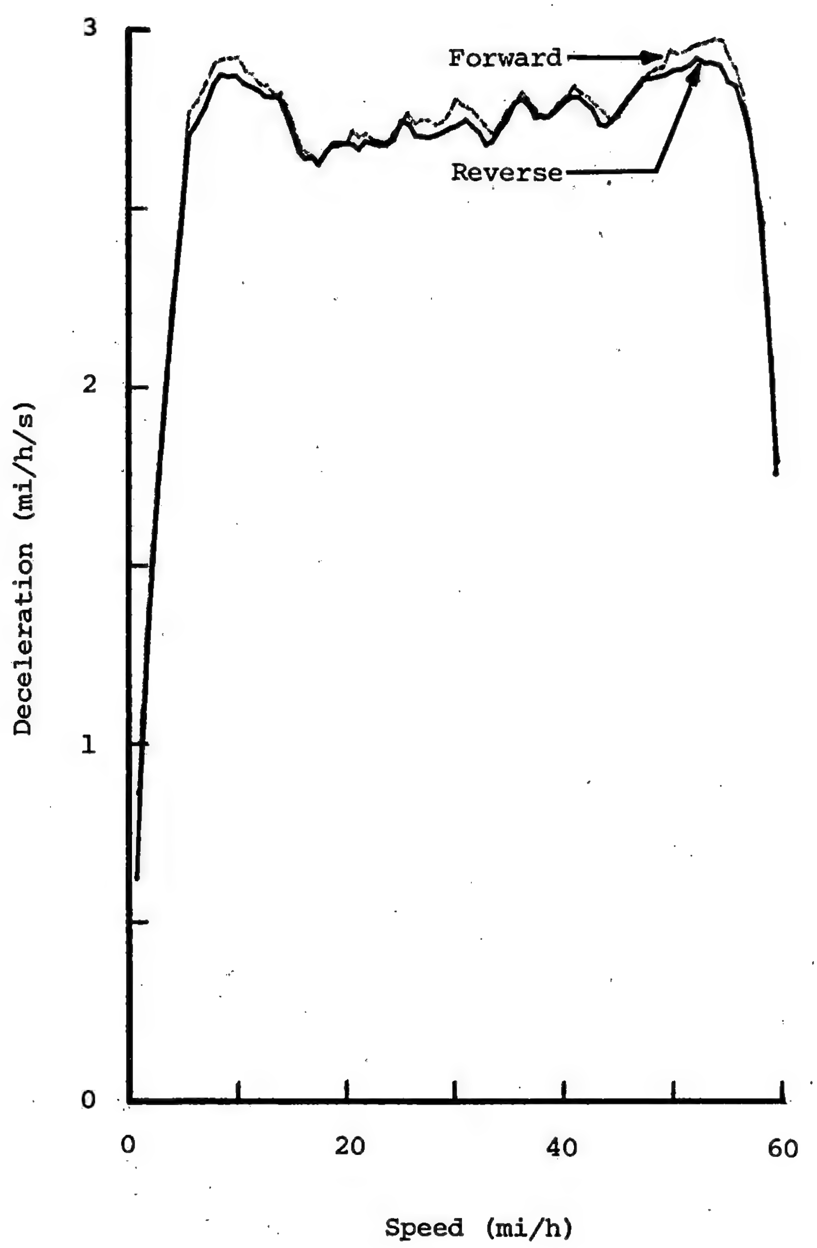

FIGURE 6-10. EFFECT OF DIRECTION ON BRAKING PERFORMANCE.

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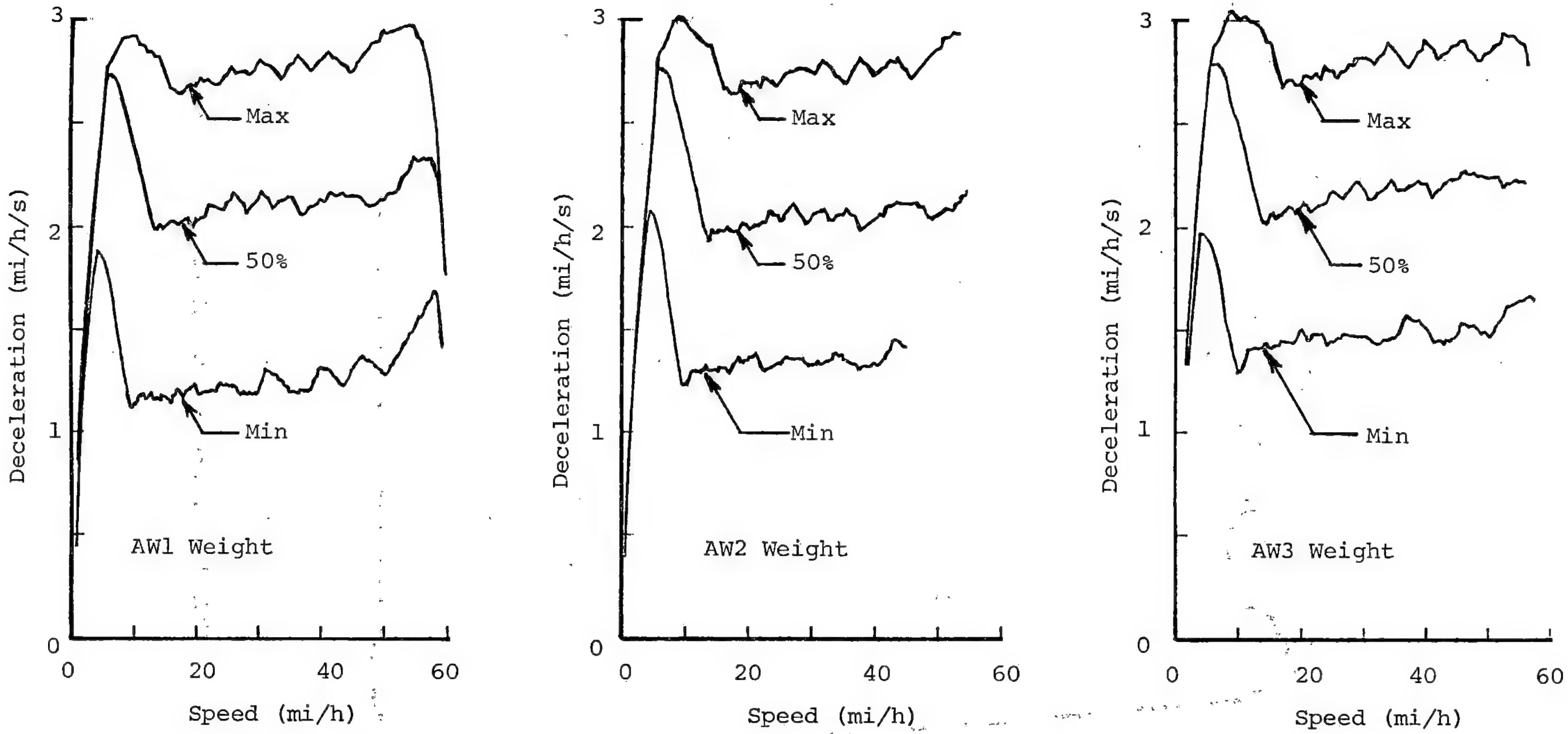


FIGURE 6-11. EP BRAKING PERFORMANCE.

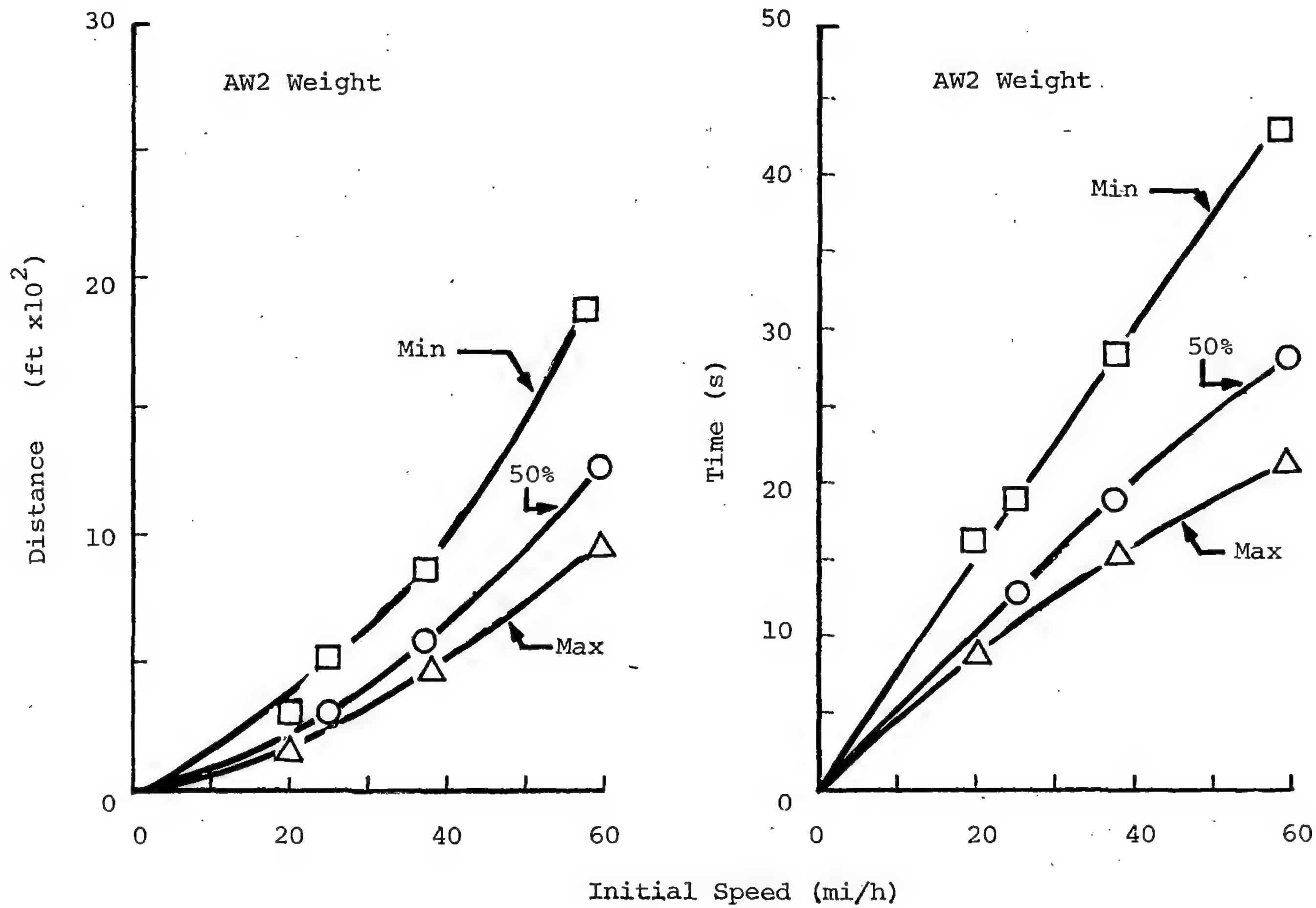


FIGURE 6-12. BLENDED BRAKING PERFORMANCE, EP MODE.

The blended brake SAP mode operated only if the EP signal had failed. As in the case of blended brake EP, retardation was carried out by both dynamic and friction brakes, except that braking was controlled by the SAP signal.

Figure 6-13 details the control characteristics for speed/deceleration at each controller setting (maximum, 50%, and minimum) for braking from 60 mi/h. Each characteristic for AW1, AW2, and AW3 is shown and each curve has been smoothed. Figure 6-14 shows the relationship between initial speed/stopping distance and initial speed/time taken to stop for the three control positions at AW2.

In comparison with blended brake EP, the blended brake SAP produced approximately 0.25 mi/h/s lower deceleration levels and required more distance and time to stop the vehicles, and did not unconditionally meet the specification requirement of 2.75 mi/h/s. Air pipe control in the EP mode is carried out by magnet valves (hence electro-pneumatic), as compared to pneumatic devices in the SAP mode. The response times in the SAP mode can be expected to be longer than those of the same system operated with magnet valves; however, the deceleration levels achieved should be independent of the method of actuation. The data available do not explain the difference in acceleration levels between EP and SAP modes. However, the SAP braking mode can be considered a backup to the EP system to provide fail-safe operation of the vehicles if the primary system should fail.

e. Dynamic-Only Braking. Test runs were carried out with the friction brakes deactivated to verify that dynamic braking met the specification requirement to be fully effective down to 15 mi/h. Friction brakes were cut in below the dynamic brake fadeout point to bring the vehicles to a stop. Figure 6-15 shows the deceleration vs. speed traces for vehicle weights of AW1, AW2, and AW3 at controller positions for minimum, 50%, and full service braking. At minimum and 50% positions, the dynamic braking was effective to less than 15 mi/h. At the maximum position, it was effective to 15-18 mi/h; i.e., it was marginally higher than the specification requirement.

f. Friction-Only Braking. The specification requires that without dynamic braking, air tread brakes in the maximum service brake position must be capable of providing the maximum blended braking deceleration rate specified for the car (2.75 mi/h/s) with an AW3 passenger load.

Figure 6-16 shows the speed/deceleration characteristics produced for friction-only EP braking at three vehicle weights from 60 mi/h. The deceleration rate in this case was generally 0.5 mi/h/s less than the required braking rate of 2.75 mi/h/s. There were some marked nonlinearities in the data as illustrated by the controller position trends. The 50% controller position produced almost as much braking effort as the maximum position; the data for AW2 showed a marked increase in deceleration rates as speed decreased from a minimum of 2.5 mi/h/s at 40 mi/h to a maximum of 2.9 mi/h/s at 15 mi/h. Figure 6-17 illustrates the stopping time and distance-to-stop trends for the friction-only SAP braking mode at AW2 weight for initial speeds from 60 mi/h.

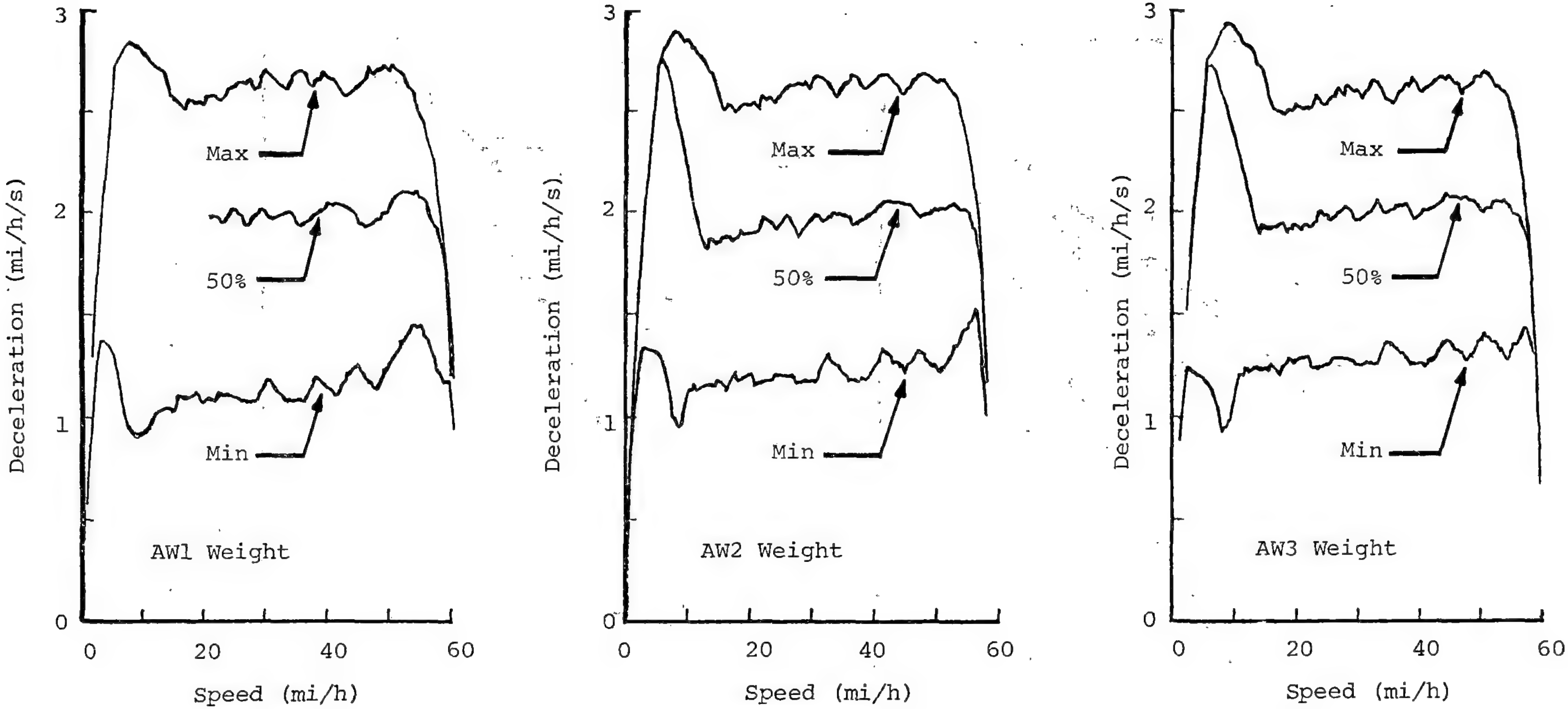


FIGURE 6-13. BLENDED BRAKING PERFORMANCE, SAP MODE.

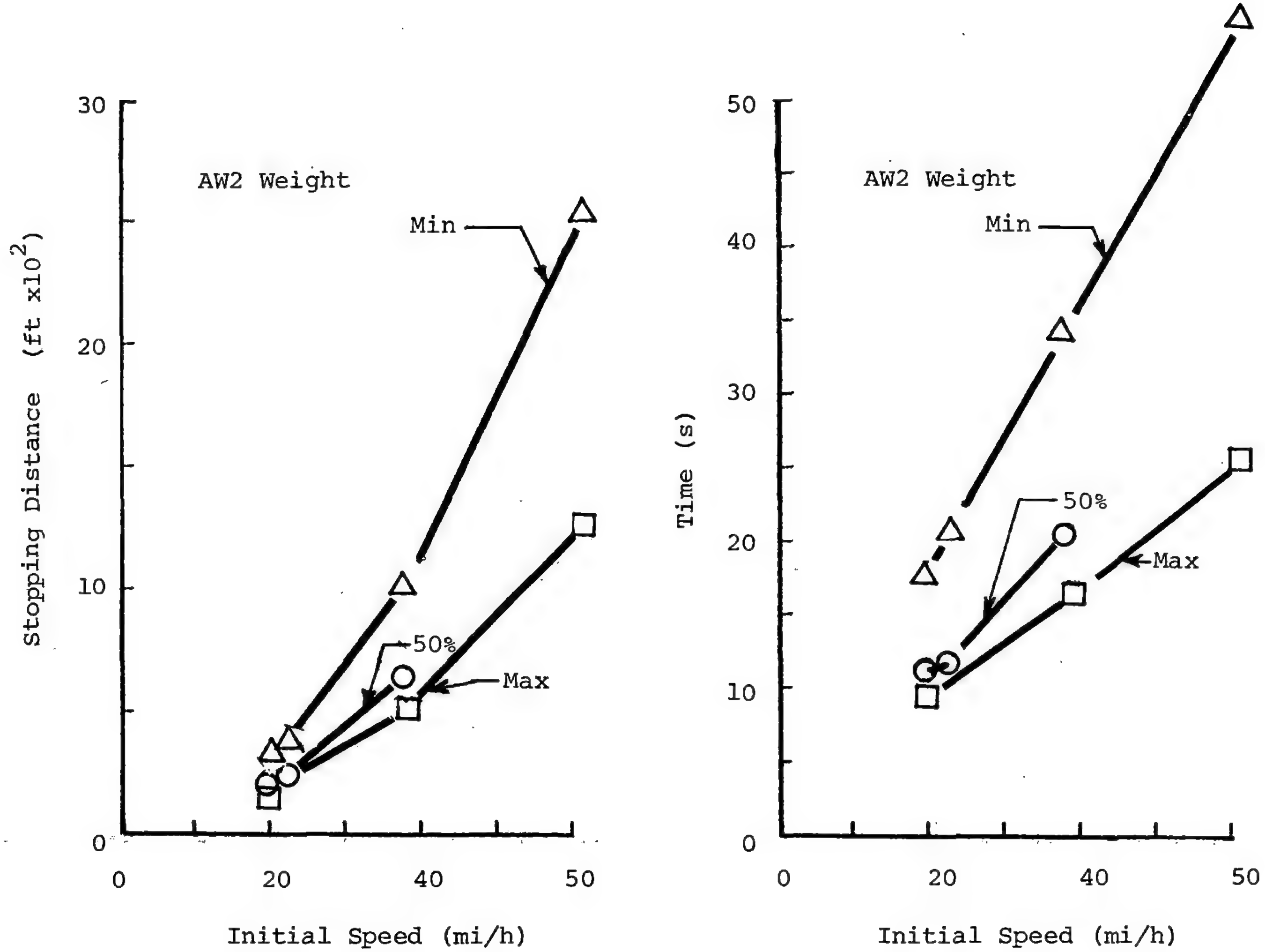


FIGURE 6-14. BLENDED BRAKING STOPPING TIME AND DISTANCE, SAP MODE.

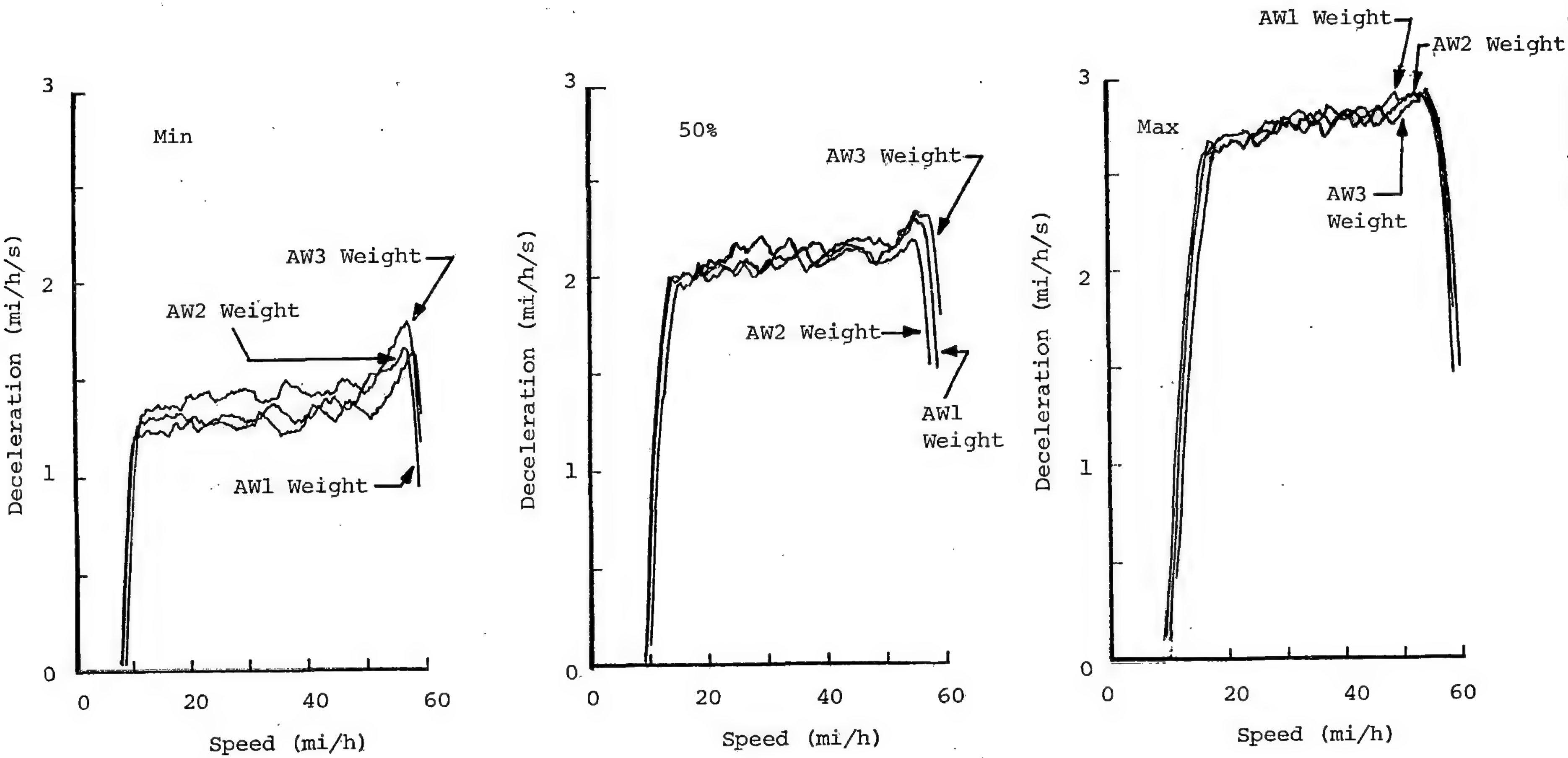


FIGURE 6-15. DYNAMIC-ONLY BRAKING PERFORMANCE.

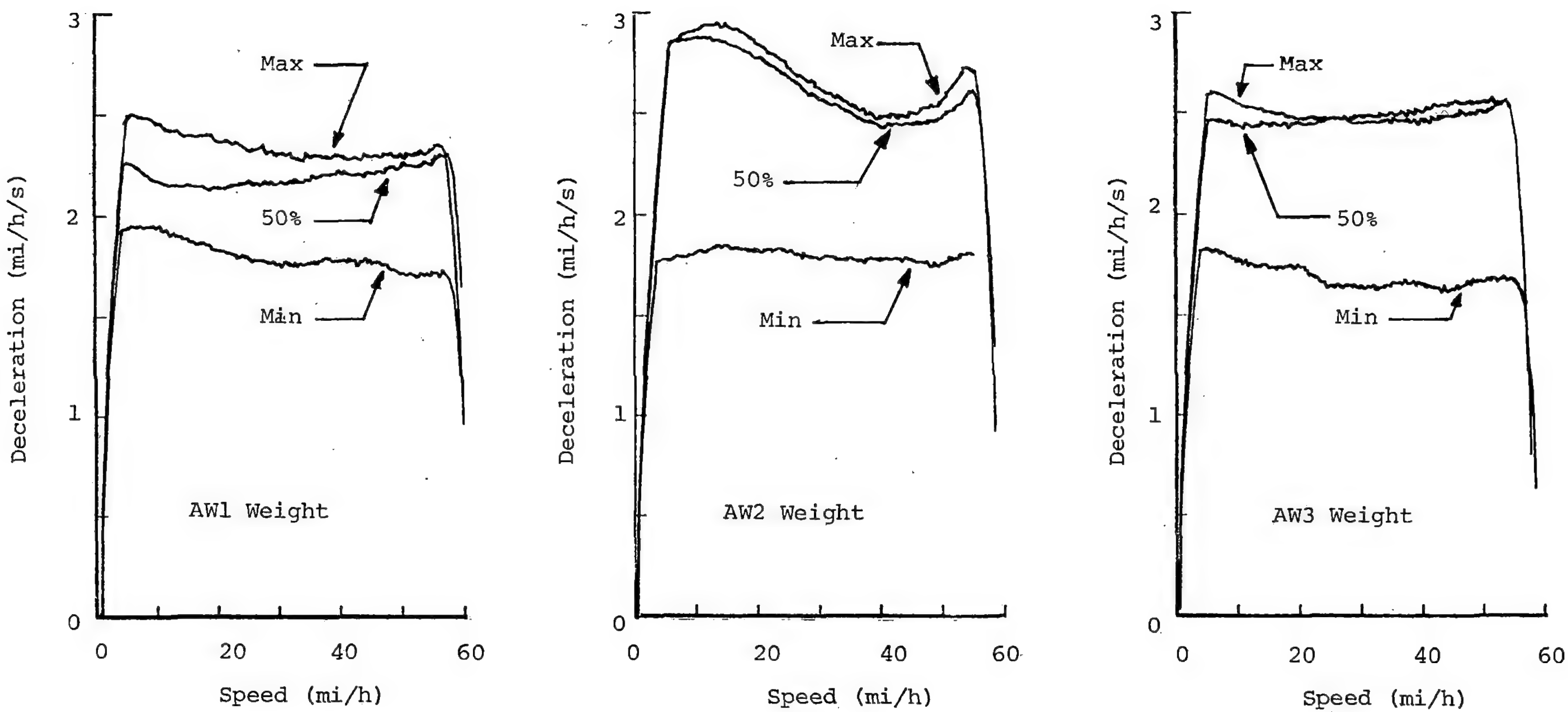


FIGURE 6-16. FRICTION-ONLY BRAKING PERFORMANCE, EP MODE.

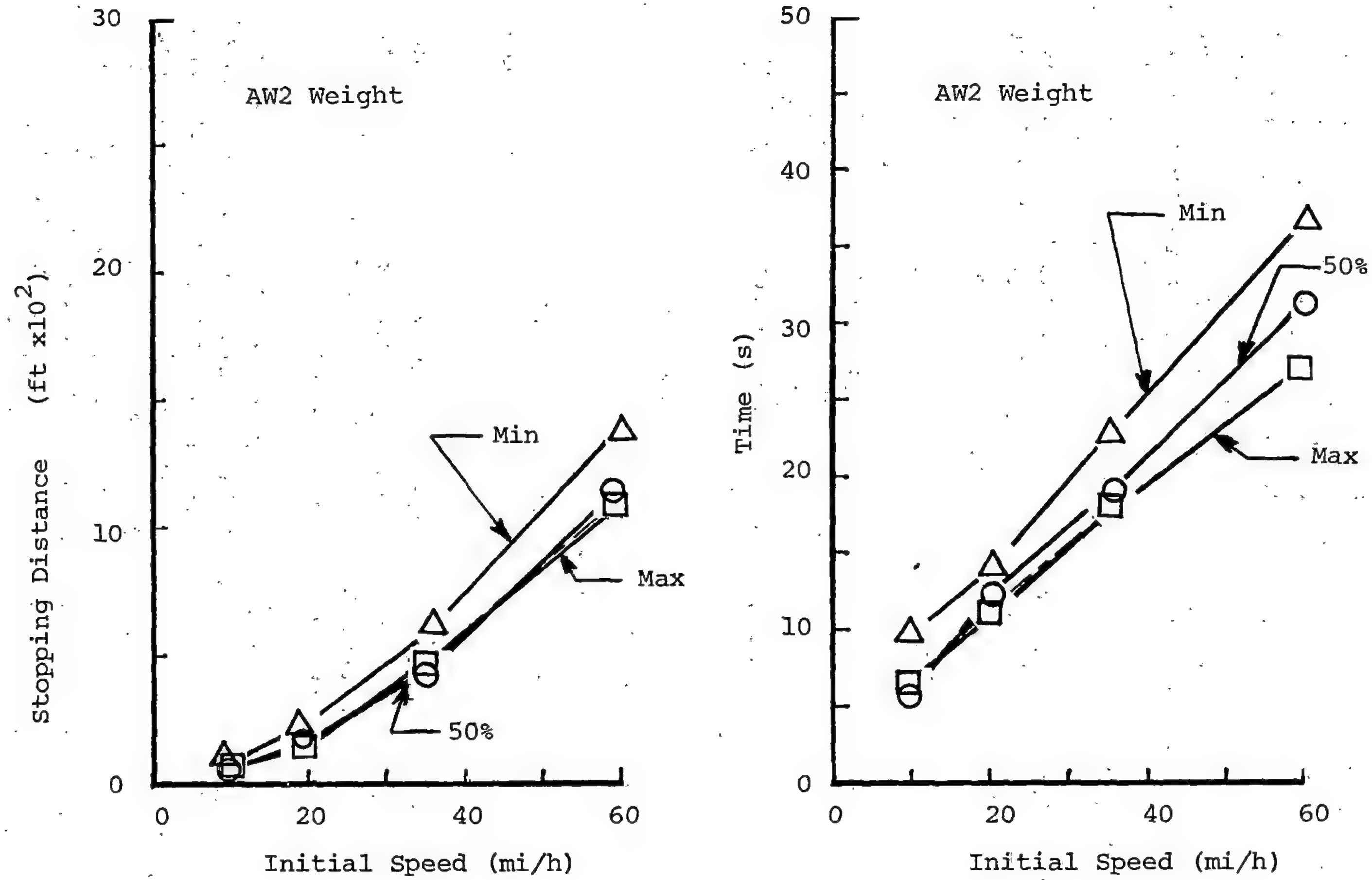


FIGURE 6-17. FRICTION-ONLY BRAKING STOPPING TIME AND DISTANCE, SAP MODE.

g. Vehicle Weight. The specification requires that for full service braking, the maximum average braking rate (2.75 mi/h/s) be maintained independent of car loading. Figure 6-18 shows the speed/deceleration characteristics for maximum brake EP and for maximum brake SAP, overlaid for AW1, AW2, and AW3 weights. It shows close matching between runs at various weights and, therefore, compliance with the specification.

h. Emergency Braking. The emergency braking mode activates friction-only brakes at a maximum level. Emergency braking can be initiated on the Blue Line vehicle in a number of ways: by releasing the operator's master controller (deadman function), by pulling the master controller back to the emergency position, or by activating the conductor's emergency valve or the trip cock. (The trip cock is a truck-mounted valve which can be activated from the wayside.) Each of these was evaluated in the emergency braking tests.

The specified emergency brake deceleration requirement for all car weights up to AW3 from 65 mi/h (or less) is 0.5 mi/h/s higher than the required maximum service rate or 3.25 mi/h/s.

The data presented in table 6-2 summarize the emergency stopping distances, times, and deceleration rates obtained for three vehicle weights (AW1, AW2, and AW3) and compare methods of initiating emergency braking. The data show that the vehicles met or were marginally under the specification requirement for an emergency braking deceleration of 3.25 mi/h/s at AW1 weight, with the exception of one trip-cock-initiated stop at 3.0 mi/h/s.

Similarly, the vehicles in general met or were marginally worse than the requirement at AW2 weight, with deceleration values in the range of 3.2 to 3.7 mi/h/s.

At AW3 weight, the vehicles failed to meet the specification requirement, with braking deceleration rates ranging from 2.8 to 3.0 mi/h/s.

Stopping distances required for deadman emergency brake applications are shown in figure 6-19, comparing distances for three vehicle weights. The distances required to stop from initial speeds of 20, 40, and 60 mi/h at weights AW1, AW2, and AW3 are plotted.

i. Jerk Rate. Jerk rates were computed by the L.T. Klauder engineer from online strip chart traces of deceleration rates. The technique optimized a mean line through the deceleration ramp by inspection, a similar line through the constant deceleration portion of the trace, and jerk rate was calculated from the slope of the deceleration ramp. A similar method was used to determine the acceleration jerk rates. Since the method of determining jerk rate is not defined in the vehicle specification, these values are reported for completeness, rather than to recommend an exact, but controversial, definition of jerk rate.

Table 6-3 summarizes the braking performance and shows the values of jerk rate derived for all modes of braking from an initial speed of 40 mi/h (the normal maximum speed of the vehicle in service), together with

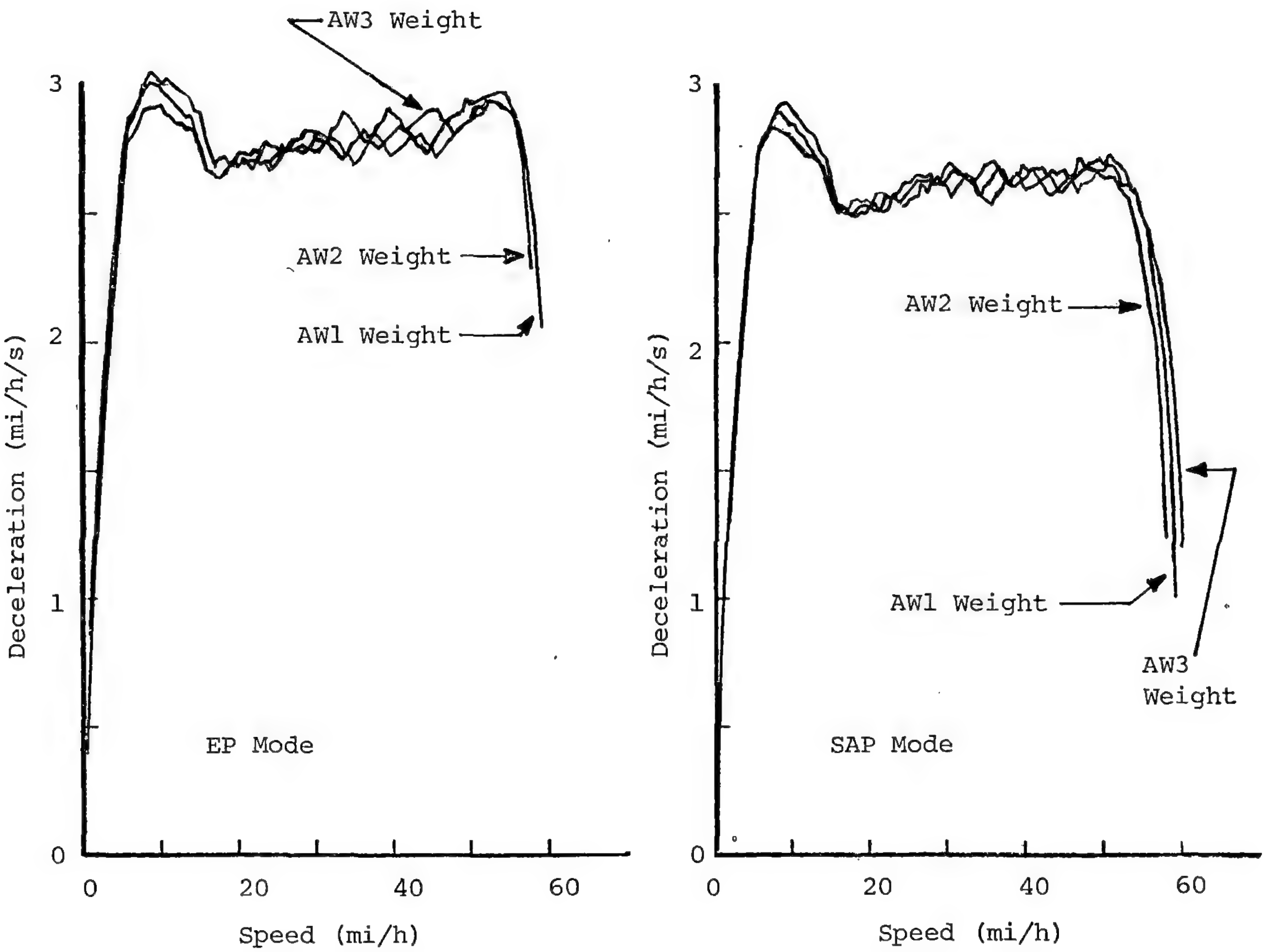


FIGURE 6-18. EFFECT OF VEHICLE WEIGHT ON FULL SERVICE BRAKING, EP AND SAP MODES.

TABLE 6-2. SUMMARY OF EMERGENCY BRAKING DATA.

Vehicle Weight AW1

Initial Speed (mi/h)	Brake Mode	Distance to Stop* (ft)	Time to Stop (s)	Average Deceleration (mi/h/s)
20	Deadman	120	7.5	3.5
40	"	440	13.5	3.5
60	"	1,000	21.5	3.2
40	Master Controller	480	14.7	3.2
40	Conductor Valve	500	15.0	3.2
40	Trip Cock	480	15.25	3.0

Vehicle Weight AW2

Initial Speed (mi/h)	Brake Mode	Distance to Stop* (ft)	Time to Stop (s)	Average Deceleration (mi/h/s)
20	Deadman	120	7.25	3.7
40	"	440	16.5	3.4
60	"	1,010	21.7	3.0
40	Master Controller	460	15.0	3.4
40	Conductor Valve	470	15.0	3.2
40	Trip Cock	470	15.0	3.2

Vehicle Weight AW3

Initial Speed (mi/h)	Brake Mode	Distance to Stop* (ft)	Time to Stop (s)	Average Deceleration (mi/h/s)
20	Deadman	125	8.5	3.0
40	"	480	15.25	3.0
60	Master Controller	1,060	16.5	2.9
40	Conductor Valve	510	16.5	2.8
40	Trip Cock	520	16.5	2.8

*Note: Data from strip charts, distance estimated from 20-ft pulses.

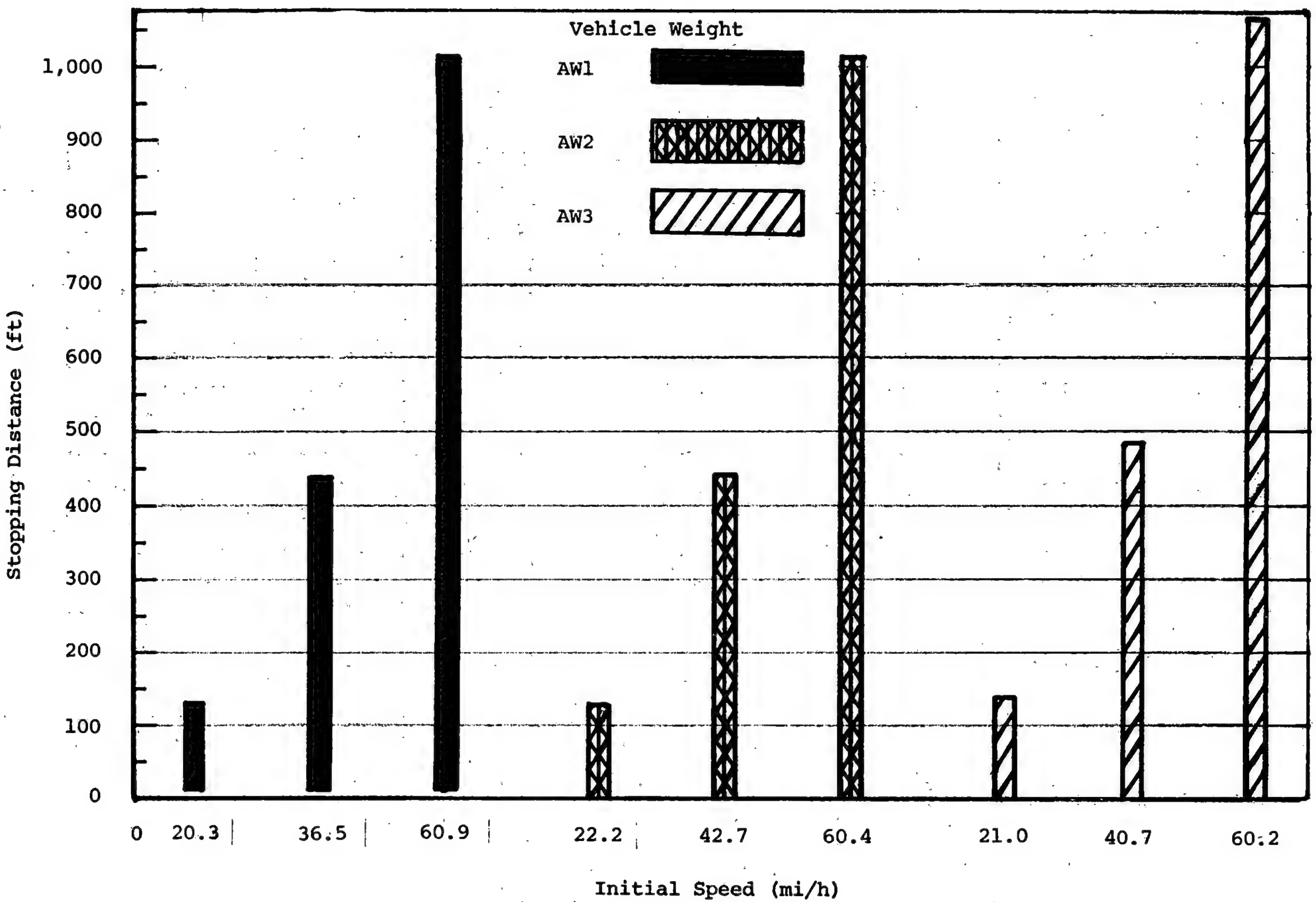


FIGURE 6-19. DEADMAN EMERGENCY BRAKING, STOPPING DISTANCES.

TABLE 6-3. COMPARISON OF DECELERATION PERFORMANCE AND SPECIFICATION REQUIREMENT.

CONTROLLER POSITION	DECELERATION PERFORMANCE (AW1 WEIGHT)			DECELERATION PERFORMANCE (AW3 WEIGHT)			SPECIFICATION REQUIREMENT (AW3 WEIGHT)		
	Decel (mi/h/s)	Decel Variation (mi/h/s)	Jerk Rate (mi/h/s^2)	Decel (mi/h/s)	Decel Variation (mi/h/s)	Jerk Rate (mi/h/s^2)	Decel (mi/h/s)	Decel Variation (mi/h/s)	Jerk Rate (mi/h/s^2)
Full Service, Blended (from 38 mi/h)	2.8	+ 0.6 - 0.3	1.9	2.8	+ 0.6 - 0.3	1.9	2.75	± 0.6	2.0
Full Service, Friction, EP (from 36 mi/h)	2.2	+ 0.3 - 0.5	2.2	2.4/2.8	+ 0.3 - 0.4	2.3	2.75	± 0.6	2.0
Full Service, Friction, SAP (from 36 mi/h)	2.2	+ 0.2 - 0.2	1.8	2.6/2.8	+ 0.3 - 0.3	2.4	2.75	± 0.6	2.0
Emergency (from 43 mi/h)	3.2/3.7	+ 0.4 - 0.2	---	2.8/3.0	+ 0.3 - 0.3	---	3.25	---	---

DYNAMIC BRAKE EFFECTIVENESS	CONTROLLER POSITION	DYNAMIC BRAKE DROP-OUT	SPECIFICATION REQUIREMENT (AW3 WEIGHT)
	MINIMUM	15 mi/h	15 mi/h
	50%	15 mi/h	
	MAXIMUM	15-18 mi/h	

the instantaneous variation of deceleration due to cam controller stepping. The vehicle specification required these values to be no greater than 2.0 $mi/h/s^2$ and 0.6 mi/h/s, respectively. The vehicles significantly exceeded the jerk rate requirement in full service friction EP braking at both AW1 and AW3 vehicle weights, and in the AW3 weight for the full service friction SAP mode. Their jerk rate was slightly below the maximum specified value for the AW1 weight in the full service friction SAP mode and blended mode, and for this latter mode, at the AW3 weight also. Since there is no jerk rate requirement for emergency braking, no performance values were computed.

6.3 DRIFT TEST (TRACTION RESISTANCE)

6.3.1 Test Objective

To determine the traction (train) resistance of the test vehicles and to verify the coefficients used in the Davis Formula to calculate their design performance.

6.3.2 Test Method

The vehicles were allowed to coast from 70 mi/h on level tangent track (stations 30.0 to 34.0) to obtain speed, time, and distance data at three vehicle weights, AW0, AW1, and AW2. The test runs were made in both CW and CCW directions on the track to minimize the effect of surface wind effects. Deceleration rates were calculated from the data for use as the source of the resistance values.

Vehicle speed fell approximately 6 mi/h for each pass through the section. In order to obtain more complete data throughout the speed range of the vehicle, consecutive passes were made with the entry speed of each pass approximating the exit speed of the previous pass. Eight passes were required to collect data for the 60 to 10 mi/h range.

Table 6-4 lists the drift runs made and the corresponding comments from the test log.

TABLE 6-4. DRIFT TEST RUN SUMMARY.

Date	Vehicle Weight	Humidity (%)	Weather	Temp. (°F)	Wind (speed/direction)	Travel (direction)	Crew Weight (est. lbs)
7-30-79	AW0	54	Clear	78	15 mi/h,east	CW and CCW	960
6-14-79	AW1	60	Clear	76	5 mi/h,west	CW and CCW	2,000
6-22-79	AW2	56	Clear	76	7 mi/h,west	CW and CCW	1,600

The analysis used recorded analog data of the drift tests, digitized at a rate of 32 samples per second (later increased to 64 in order to be certain of capturing ALD markers). Engineering unit tabulations were then made in the standard performance format, recording every thirty-second sample of each variable. This procedure produced listings at 1-second intervals.

Figure 6-20 shows a typical trace for an AW0 clockwise pass through the drift section. The usable data spanned a range of 59.5 to 51.5 mi/h; the rate of deceleration was approximately 0.17 mi/h/s. Ripples inherent in the trace are due to fluctuations in velocity caused by flange contact, wind, interaction between the two vehicles, etc., or velocity transients resulting from the manner in which the velocity signal was derived.

Initially, an attempt was made to blend individual passes of each drift run into one complete trace from 60 to 10 mi/h. It was then intended to curve-fit the composite trace with a second order polynomial curve. This was only partially successful and the method was dropped in favor of a "moving average" method in which, for any given pass, the first group of 20 data pairs (points 1-20) of velocity and time were fitted with a straight line using the least squares method. This yielded a mean value of deceleration (the slope), which was assigned to the average value of velocity for the group. The data pair of deceleration and velocity was then plotted. This process was repeated with a second group of 20 data pairs (points 2-21), which yielded a second data pair of deceleration and velocity. The pattern was repeated with successive groups of 20 data points, and the resulting data pairs of deceleration and velocity for each pass were plotted as shown in figure 6-21. The figure shows typical data produced from seven successive passes through the section in a CCW direction, AW0 weight. The data pairs were then fitted with a polynominal curve of the form:

$$\text{Deceleration} = A_0 + A_1V + A_2V^2,$$

where:

V = speed (mi/h) and

A_0, A_1, A_2 = coefficients of the polynominal curve, again by the least squares method.

This curve was chosen because it follows the Davis approach of modeling train resistance, where the three coefficients represent rolling resistance, flange effects, and aerodynamic resistance. See appendix B for further discussion. Plots were also made for merged CW and CCW data (figure 6-22).

Table 6-5 shows coefficients produced by these curve fits for each vehicle weight and vehicle direction in the curve fit.

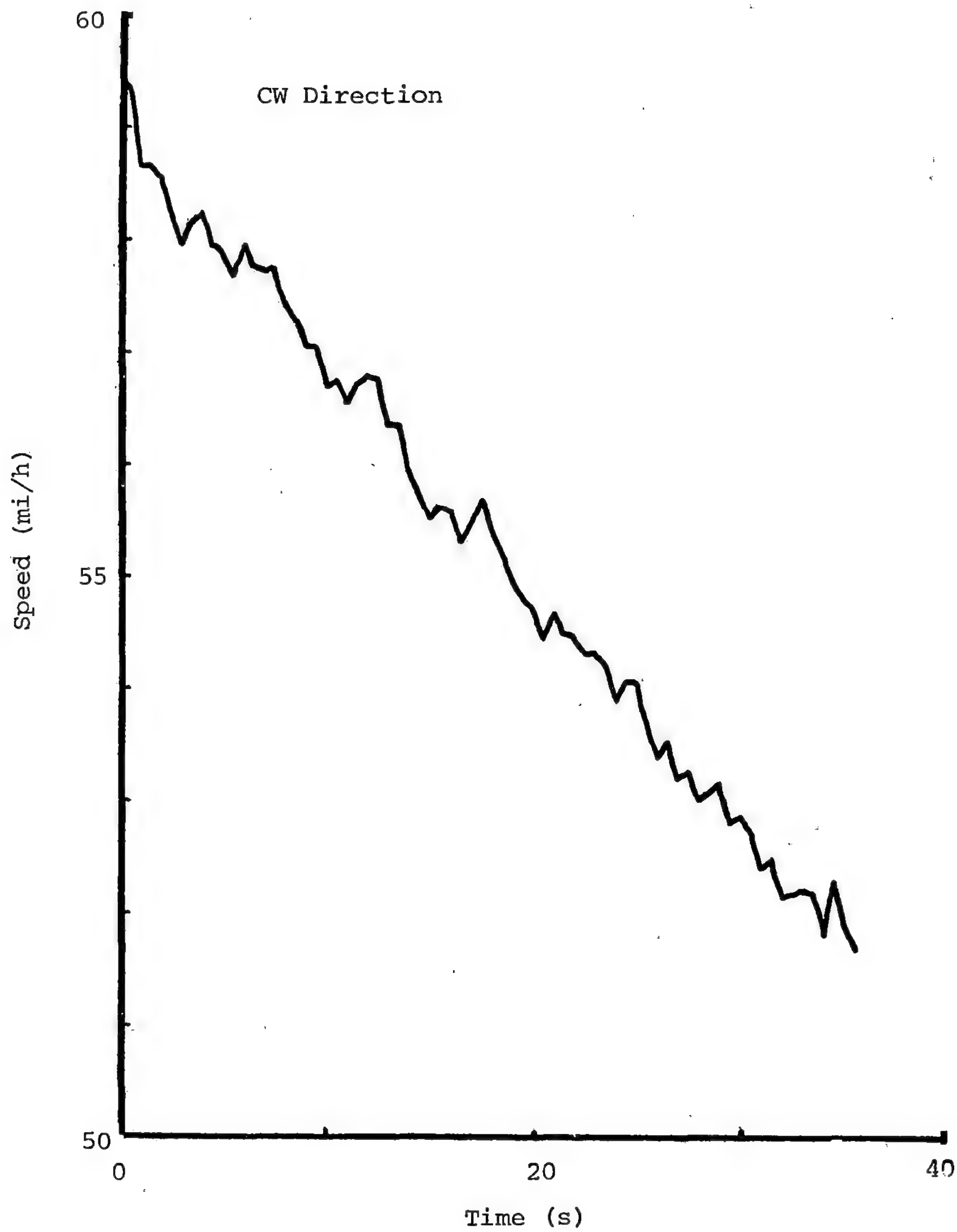


FIGURE 6-20. TYPICAL PASS THROUGH DRIFT SECTION, AW0 WEIGHT.

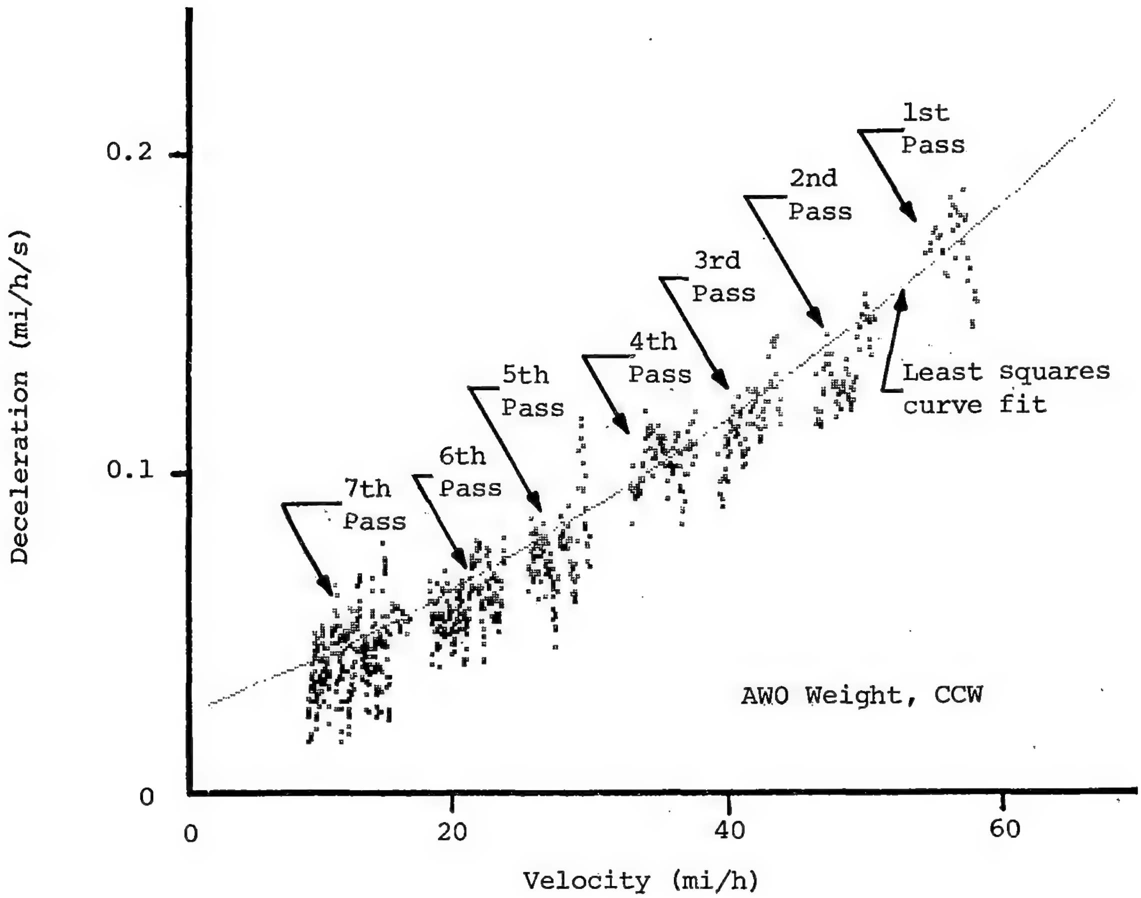


FIGURE 6-21. VELOCITY AND DECELERATION PAIRS FROM SEVEN SUCCESSIVE PASSES.

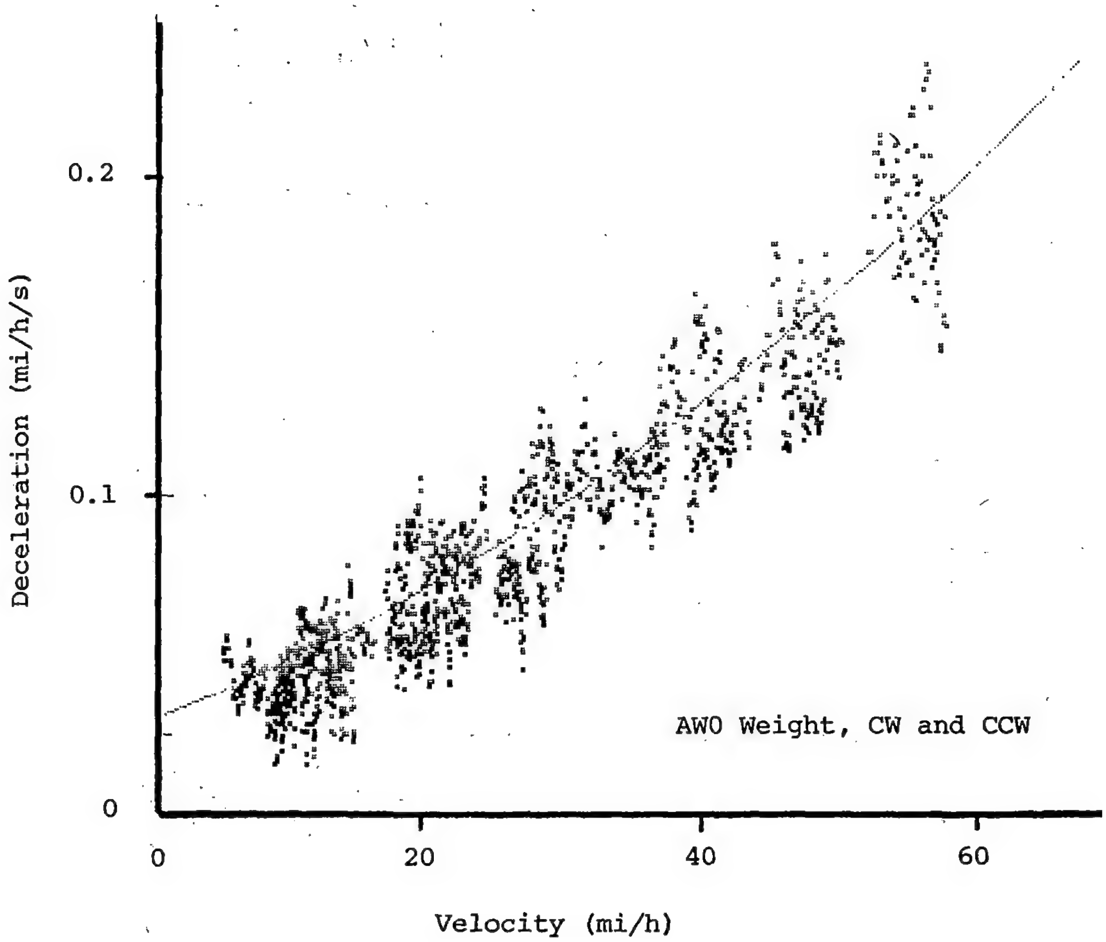


FIGURE 6-22. VELOCITY AND DECELERATION PAIRS PRODUCED BY MERGING CW AND CCW PASSES.

TABLE 6-5. TABLE OF COEFFICIENTS.

Weight	Direction	A_0	A_1	A_2
AW0	CW	0.033	0.0020	1.171×10^{-5}
	CCW	0.025	0.0016	1.729×10^{-5}
	Composite	0.030	0.0016	2.057×10^{-5}
AW1	CW	0.048	-0.0001	3.862×10^{-5}
	CCW	0.033	0.0014	2.238×10^{-5}
	Composite	0.040	0.0006	2.969×10^{-5}
AW2	CW	0.037	0.0007	3.910×10^{-5}
	CCW	0.027	0.0007	2.873×10^{-5}
	Composite	0.027	0.0011	2.699×10^{-5}

The composite coefficients of A_0, A_1, and A_2 were derived by merging CW and CCW data which were then curve-fitted. The values of composite cases were used for further analysis.

Train resistance to motion, produced by rolling resistance, flange effects, and aerodynamic drag, acted on the married pair of vehicles and retarded them according to Newton's First Law (deceleration is directly proportional to the resistance force). However, a weight allowance was added for the rotating parts of the vehicle to represent angular inertia, and was estimated as being equivalent to 10% of the vehicle weight, which added to the mass inertia of the train. Thus, if R is the train resistance and F the vehicle deceleration, then at any time during a drift run:

$$R = \frac{F(W + W_E)}{g} \tag{1}$$

where:

g = acceleration due to gravity (21.94 mi/h/s),

W = weight of the married pair (lbs), and

W_E = equivalent weight of the rotating parts (lbs).

Figure 6-23 applies equation (1) to deceleration rates to show the relation of train resistance force vs. velocity for AW0, AW1, and AW2 weights:

$$\text{Train resistance R (lbs)} = (A_0 + A_1V + A_2V^2)\,\frac{(W + W_E)}{g}$$

Note that curves were drawn only for the range where data were available. It can be seen that the results do not show a family of smooth curves and do not produce the expected rank by weight of AW0, AW1, and AW2. This suggests that while the curve fits give a good approximation of the overall train resistance of the Blue Line cars, individual resistance components due to flange effects and aerodynamic resistance cannot be identified with any confidence because of scatter in the experimental data. Appendix B contains a comparison of experimental results with the prediction method discussed in the vehicle specifications.

The vehicles (2-car train) had the resistance characteristics detailed in table 6-6.

TABLE 6-6. TRAIN RESISTANCE CHARACTERISTICS.

Vehicle Weight	Weight (lbs) W	Estimated Equivalent Weight of Rotating Parts(lbs) W_E	Total (lbs) $W+W_E$
AW0	122,600	12,000	134,600
AW1	128,860	12,000	140,860
AW2	139,180	12,000	151,180

6.4 DUTY CYCLE-FRICTION BRAKES

6.4.1 Test Objective

To evaluate the equilibrium temperature of the friction brake components under continuous duty cycle operation in the event of dynamic brake malfunction, over a simulated Blue Line service run and two others representing New York City and Cleveland revenue service runs.

6.4.2 Test Method

Three duty cycle profiles were used to evaluate the vehicles' friction brake system:

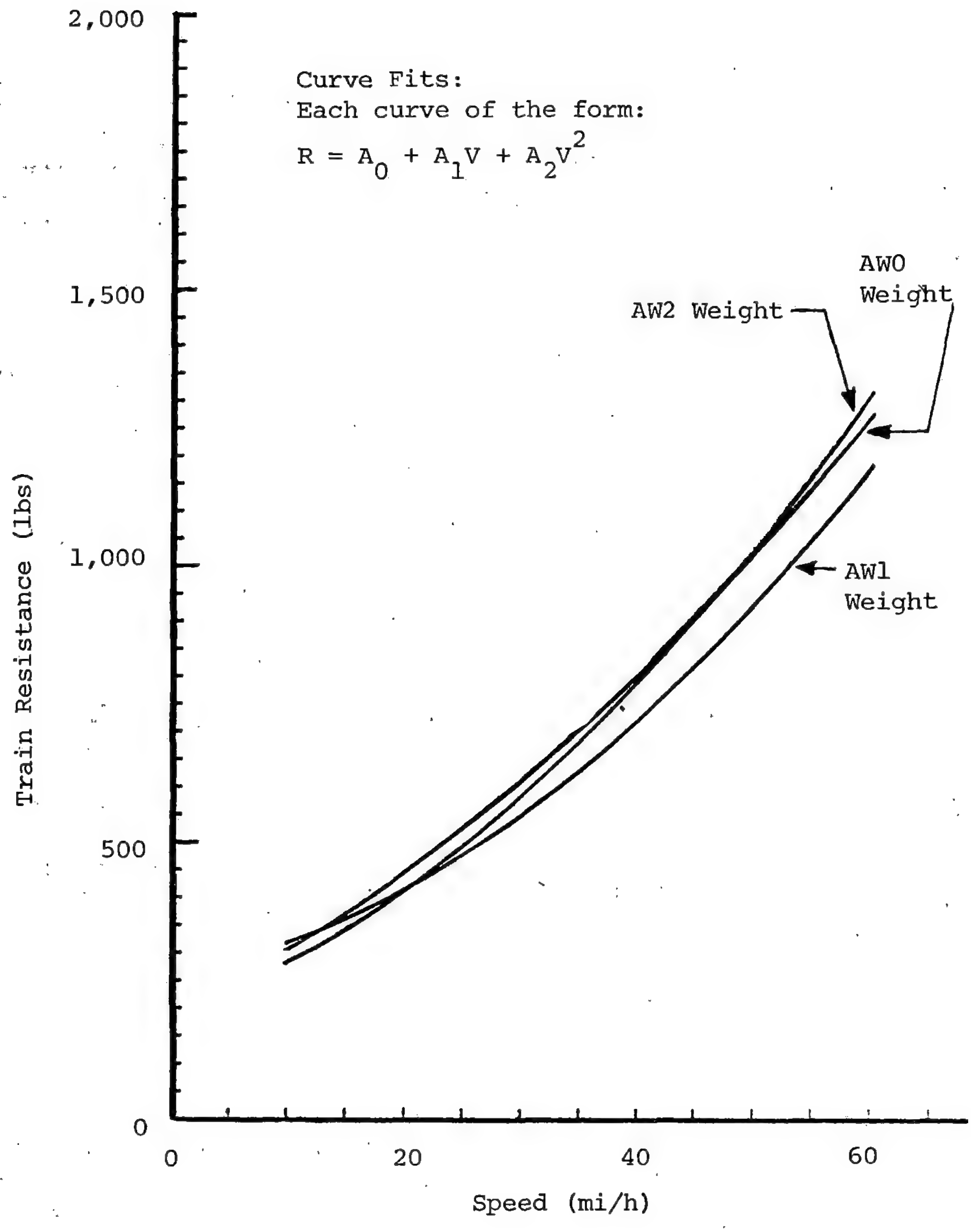


FIGURE 6-23. COMPARISON OF TRAIN RESISTANCE AND SPEED BY VEHICLE WEIGHT.

- A simulation of the MBTA Blue Line route with 22 station stops and a maximum speed of 40 mi/h; the MBTA Blue Line profile is listed in table 6-7, with additional information concerning the test runs in appendix C.
- A duty cycle typifying NYCTA operation. The run comprised an acceleration to 35 mi/h, constant speed for 45 seconds, and brake to a full stop, followed by a 30-second station stop; the sequence was repeated for 16 cycles.
- A duty cycle typifying Cleveland Transit System (CTS) operation. The run comprised an acceleration to 50 mi/h, constant speed for 55 seconds, and brake to a full stop, followed by a 30-second station stop; the sequence was repeated for 12 cycles.

Embedded and hand-held thermocouples (figure 6-24) were used to measure temperature, and the following measurements were taken:

Location	Description
1	Thermocouple embedded in the brake shoe 1/8" above the interface between shoe and tread.
2	Thermocouple attached with adhesive tape to the side of the brake shoe.
3	Hand-held thermocouple probe at the side of the brake shoe.
4	Hand-held thermocouple probe on the side of the wheel close to the tread.

The thermocouple and probe measurements were taken on the cab-end truck of car 0609.

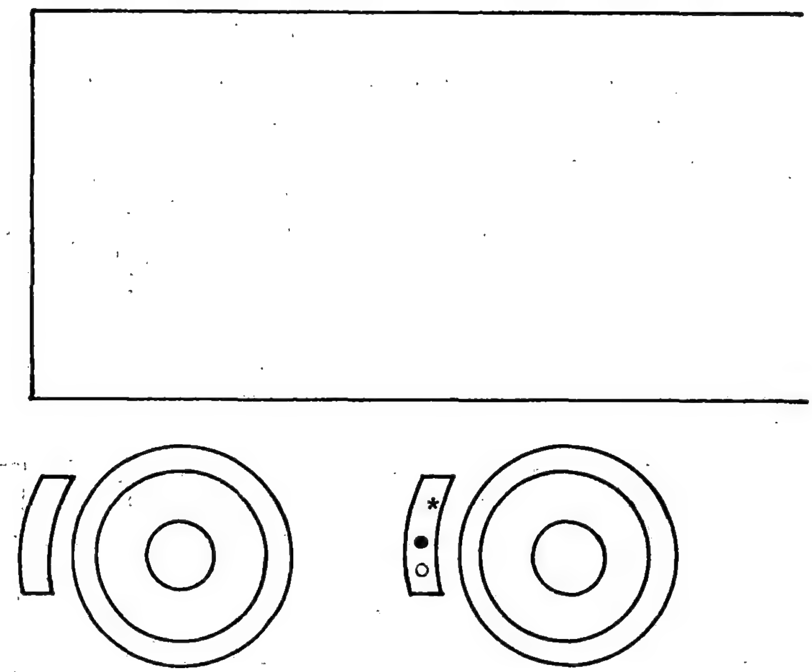
Full service acceleration and braking were used for all duty cycle testing, using friction-only braking. Note that the cab-end truck of car 0609 was leading for half of the MBTA route and trailing for half. For NYCTA and CTS duty cycles, it was always the lead truck.

6.4.3 Test Results

Figure 6-25 shows the brake thermal characteristics over the Blue Line route simulation, coincident with the vehicles' speed/time histogram. The hand-held thermocouple probe readings were taken within 30 seconds of station stops; embedded thermocouple sensors gave continuous readings but have been plotted every 10 seconds. Similar overlay plots of time vs. speed and temperature for the other two profiles tested are also shown in the figure.

TABLE 6-7. MBTA BLUE LINE PROFILE.

DEPART STATION	DISTANCE (ft)	ARRIVE STATION	STOP TIME
Bowdoin	900	Government Ctr.	30 s
Government Ctr.	900	State	30 s
State	1,470	Aquarium	30 s
Aquarium	4,700	Maverick	30 s
Maverick	2,500	Airport	30 s
Airport	2,460	Wood Island	30 s
Wood Island	4,620	Orient Heights	30 s
Orient Heights	2,290	Suffolk Downs	30 s
Suffolk Downs	2,460	Beachmont	30 s
Beachmont	3,100	Revere Beach	30 s
Revere Beach	1,700	Wonderland	2 min
Wonderland	1,680	Revere Beach	30 s
Revere Beach	3,180	Beachmont	30 s
Beachmont	2,380	Suffolk Downs	30 s
Suffolk Downs	2,260	Orient Heights	30 s
Orient Heights	4,520	Wood Island	30 s
Wood Island	2,660	Airport	30 s
Airport	2,380	Maverick	30 s
Maverick	4,700	Aquarium	30 s
Aquarium	1,470	State	30 s
State	950	Government Ctr.	30 s
Government Ctr.	900	Bowdoin	END



o = Thermocouple on surface of shoe.

● = Thermocouple embedded in shoe = 1/8" from wheel tread.

* = Hand-held thermocouple readings taken with Extech digital readout temperature probe, NiCr/NiAl-type probe.

Located on car 0609, cab-end truck, left side.

FIGURE 6-24. THERMOCOUPLE LOCATIONS, CAR 0609.

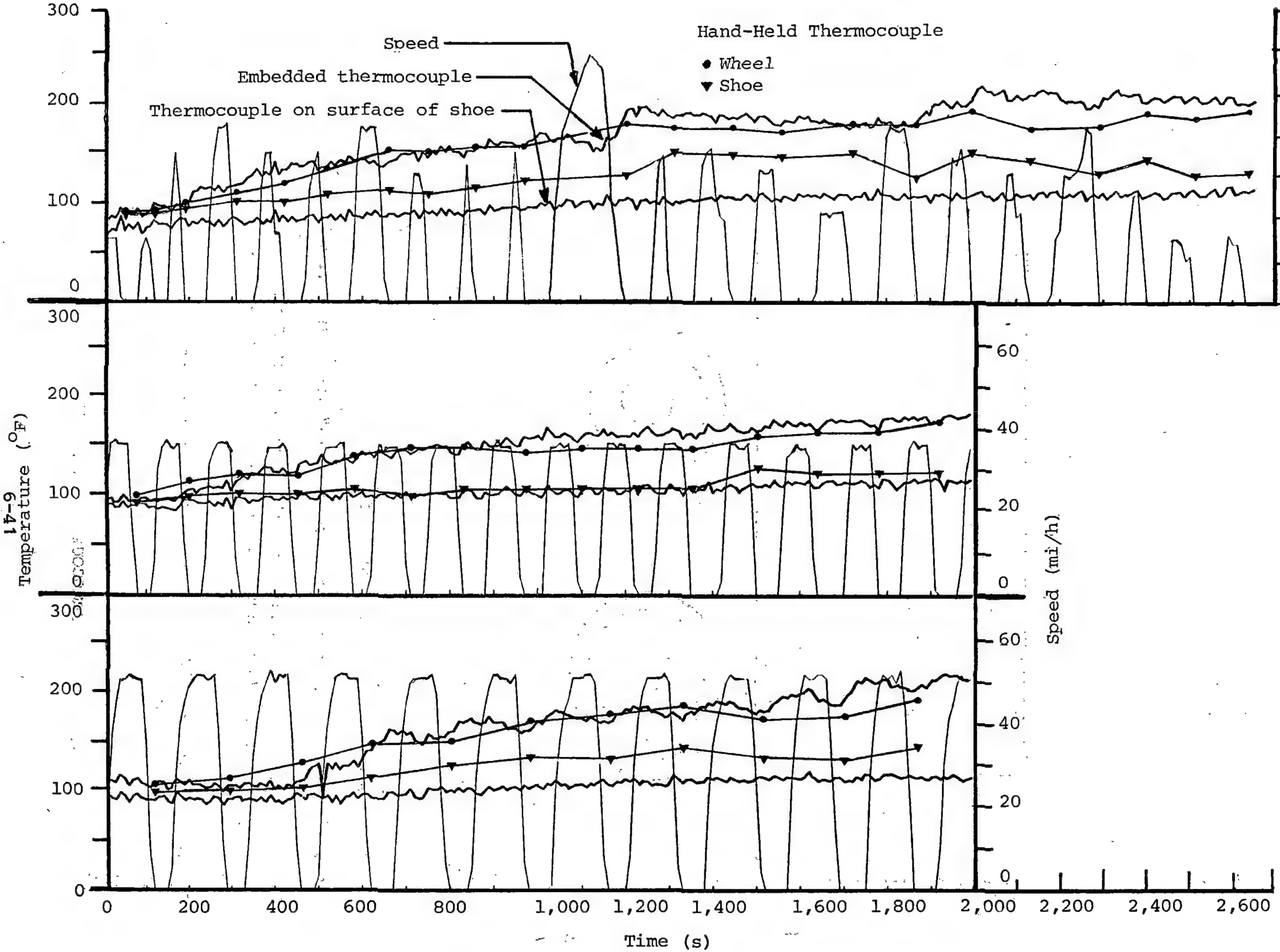


FIGURE 6-25. FRICTION BRAKE DUTY CYCLE, MBTA BLUE LINE, NYCTA "A" TRAIN, AND CTS PROFILES.

The resulting equilibrium temperatures for the four locations and three profiles are shown in table 6-8.

TABLE 6-8. EQUILIBRIUM TEMPERATURES.

Location	Temperature °F		
	MBTA	NYCTA	CTS
1 Embedded, shoe	202	190	212
2 Taped-to-shoe	117	120	115
3 Hand-held, shoe	130	120	140
4 Hand-held, wheel	197	178	192

Brake shoe temperatures measured by the hand-held and taped-to-shoe thermocouples were 70-90°F less than temperatures measured by the embedded thermocouple. This difference is probably caused by the relatively poor thermal conductivity characteristics of the brake shoe material.

Test results show that brake and wheel temperatures stabilized at approximately 200°F during a simulated friction-only braking duty cycle run representing the Blue Line. The brakes may reach different equilibrium temperatures in service, due to differences between the service environment and that of the TTC.

6.5 ENERGY CONSUMPTION

6.5.1 Test Objective

To evaluate vehicle energy requirements and schedule performance over a series of simulated revenue service profiles.

6.5.2 Test Method

Four revenue service profiles were simulated for these tests. They were test runs comprising a series of station stops; the distances, speeds, and times between stations were fixed to match an actual revenue run. The track grades of the revenue routes could not be reproduced, and so the revenue service profiles were simulations only, used as a standardized base to obtain comparative energy consumption data. The profiles simulated a Washington

Metropolitan Area Transit Authority (WMATA) route from Grosvenor to Metro Center and Silver Spring to Metro Center (17.08 mi), a NYCTA "A" train from 207th street to Boyd Avenue (21.73 mi), the MBTA Blue Line (9.96 mi), and a simulated line profile for the Advanced Concept Train (ACT-1) (18.08 mi). These profiles are detailed in appendix C.

All profiles were run at AW2 vehicle weight. Onboard watt-hour meters measured the energy consumed for each profile (appendix A, section 3.2).

6.5.3 Test Results

Figure 6-26 is a typical overlaid plot of time/speed, time/line voltage, and time/energy consumed, produced from data listed every five seconds. It can be seen that the instantaneous line voltage is dependent on the vehicles' position on the track as well as vehicle energy demand. Note also that power was drawn to supply auxiliaries when the vehicle was stationary. The energy consumed for each profile was recorded from the onboard wattmeters, and is listed in table 6-9.

TABLE 6-9. ENERGY CONSUMED, AW2 WEIGHT.

Profile	Distance (mi)	Max Speed (mi/h)	Car 608 (kWh)	Car 609 (kWh)	Total Energy (kWh)	Energy per mile (kWh/mi)
WMATA	17.08	65	106.65	87.75	194.4	11.38
NYCTA A	21.73	35	133.5	108.45	241.95	11.13
MBTA Blue	9.96	44	63.9	53.85	117.75	11.82*
MBTA Blue	9.96	44	66.75	54.75	121.5	12.20*
ACT-1	18.08	65	129.0	112.35	241.35	13.35

* This variation of energy consumption for the same revenue profile simulation is attributed to random operation of the vehicle auxiliaries.

As part of the special engineering test program, further energy consumption tests were conducted to evaluate methods of reducing energy required to operate the vehicle on the MBTA Blue Line. These tests are discussed in section 9.2.

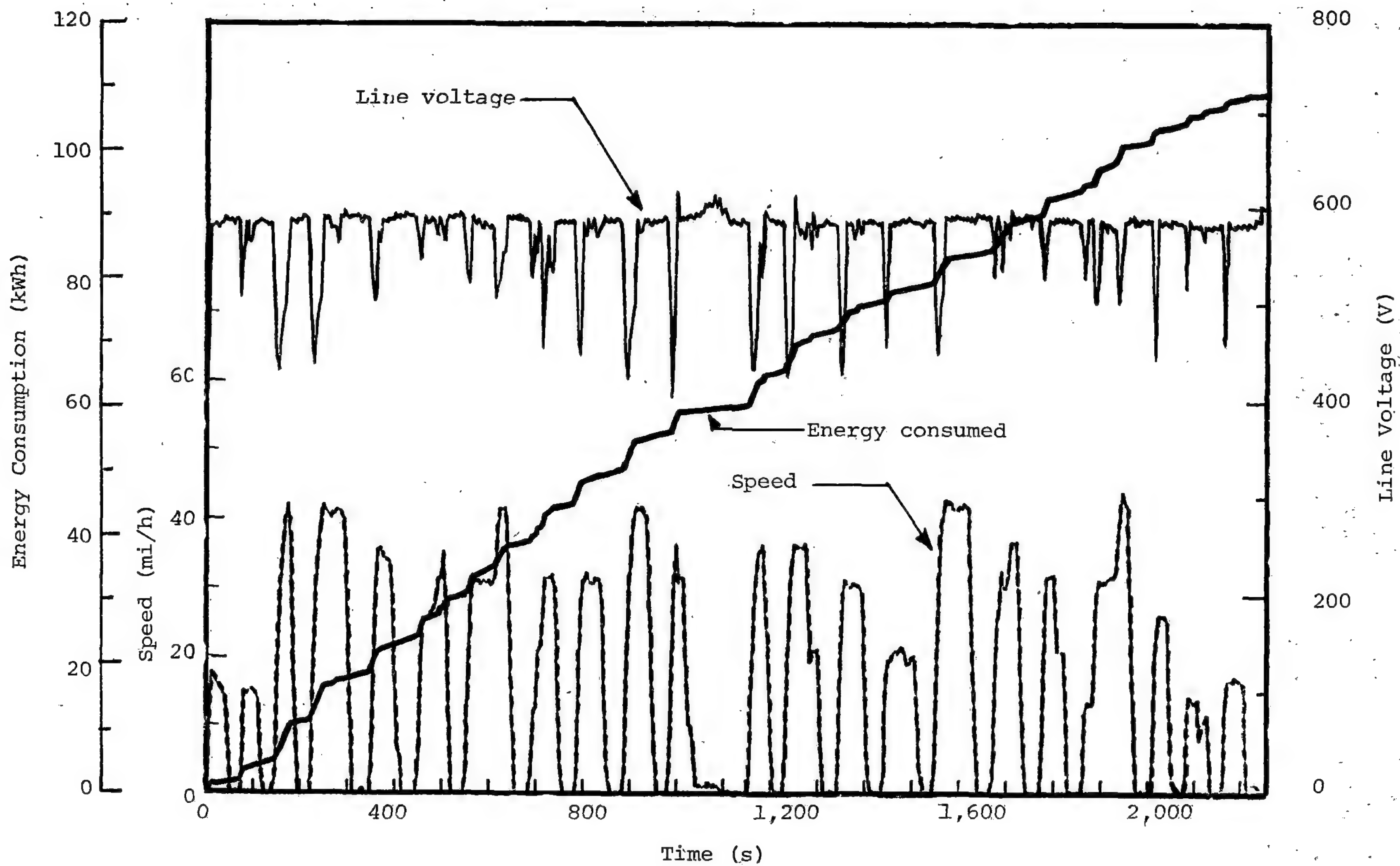


FIGURE 6-26. ENERGY CONSUMPTION PROFILE, MBTA BLUE LINE.

It should be noted that there is one fundamental difference between the energy consumption data presented here and that of the energy conservation program. Here, the energy consumption includes that used by the vehicle auxiliaries; i.e., compressor, motor generator set, etc., but excluding the air conditioning. In the latter, only energy required by the propulsion system was measured.

Results and Discussion

7.0 NOISE TESTS

The purpose of the noise tests was to characterize noise levels generated by the operation of the Blue Line cars, at the wayside and inside the vehicles.

Tests were conducted to evaluate the wayside noise levels due to the operation of vehicles' auxiliary equipment with the vehicles stationary, and to establish the noise levels generated by the two-car train passing a wayside location at constant speeds. A noise survey of the vehicles' interior was conducted at a constant speed to determine the worst locations. The effects of speed, track section, acceleration, and deceleration were evaluated for selected interior locations, based on the results of the noise survey.

7.1 WAYSIDE NOISE TESTS

7.1.1 Test Objective

To determine the contribution of auxiliary equipment noise to the total vehicles' signature, and to evaluate wayside noise levels due to the Blue Line cars passing a wayside station at constant speeds.

7.1.2 Test Method

Measurements of sound levels were taken using a B&K type 2203 sound level meter. Maximum meter readings were manually recorded for each test with the instrument set to display A-weighted sound levels (dBA re $2x10^{-5}$ N/m^2) on a "slow" response setting. Three microphone locations were used to evaluate noise generated by the auxiliary equipment:

Location	Description
1	On the platform at ear level, 5 ft from the side of car 0608, midway down the car.
2	On the platform at ear level, 5 ft from the side of car 0609, midway down the car.
3	50 ft from the track centerline, at ear level, between the two cars.

Two microphone locations were used to evaluate the effect of vehicle speed on wayside noise. They were located 50 ft from the track centerline, one inside the TTT oval, and the other outside adjacent to a section of tangent track with welded rail and concrete ties.

Test Variables. The stationary tests were conducted with the vehicles' motor generator, air compressor, air conditioning fans and units, doors, and brake release valves operating in combinations given in table 7-1.

The constant speed tests were conducted at speeds of 20, 30, 40, 50, and 60 mi/h at vehicle weights of AW1, AW2, and AW3. The vehicles made passes with and without traction motor shrouds fitted. These shrouds were experimental, produced by General Electric, the traction motor manufacturer, with the objective of attenuating traction motor noise.

7.1.3 Test Results

The noise levels for the various combinations of auxiliary equipment are presented in figure 7-1, recorded midway down each car at 5 ft from the side of the car, and at 50 ft from the track centerline. It should be noted that the air compressor is located in car 0609 and the motor generator in car 0608. This caused large differences in the 5 ft noise levels between cars when these auxiliaries were operating. Wayside noise levels were below 70 dBA with the exception of momentary peaks up to 82 dBA adjacent to car 0608, due to brake release. The cars met the vehicle specification noise level criterion of 80 dBA at 50 ft, while stationary with auxiliary systems operating.

Noise levels at 50 ft from the track centerline due to the cars' passing at constant speeds from 20 to 60 mi/h, at three vehicle weights, are presented in figure 7-2. The figure shows that the noise level increases with speed from approximately 72 dBA at 20 mi/h to 85-90 dBA at 60 mi/h with no significant trends due to vehicle weight. The vehicles' specification criterion for wayside noise levels, 80 dBA at 50 ft, is required only for speeds up to 40 mi/h, and this requirement was met. Noise levels for speeds in excess of 40 mi/h marginally exceeded the 80 dBA level. Noise levels inside and outside the TTT oval were similar, indicating similar levels of sound emission from each side of the vehicles.

Tests conducted with traction motor shrouds fitted showed no detectable differences in the wayside noise levels at 50 ft from the track.

The vehicles' warning horn produced wayside noise levels of 102-105 dBA.

7.2 INTERIOR NOISE TESTS

7.2.1 Objectives.

To determine noise level trends with vehicle speed and track location, and the noise levels during acceleration and braking. An additional objective was to conduct a noise level survey of the car interior to determine noise levels throughout the vehicles under typical operating conditions.

TABLE 7-1. EQUIPMENT OPERATING DURING WAYSIDE NOISE TESTS.

Combination No.	Third Rail	Motor Generator Set	Air Compressor	Air Conditioning Evaporating Fans	Air Conditioning Units	Cycling Doors	Brake Release Application
1	X						
2	X	X					
3	X	X	X				
4	X	X		X			
5	X	X	X	X			
6	X	X		X	X		
7	X	X	X	X	X		
8	X	X		X	X	X	
9	X	X		X	X		X

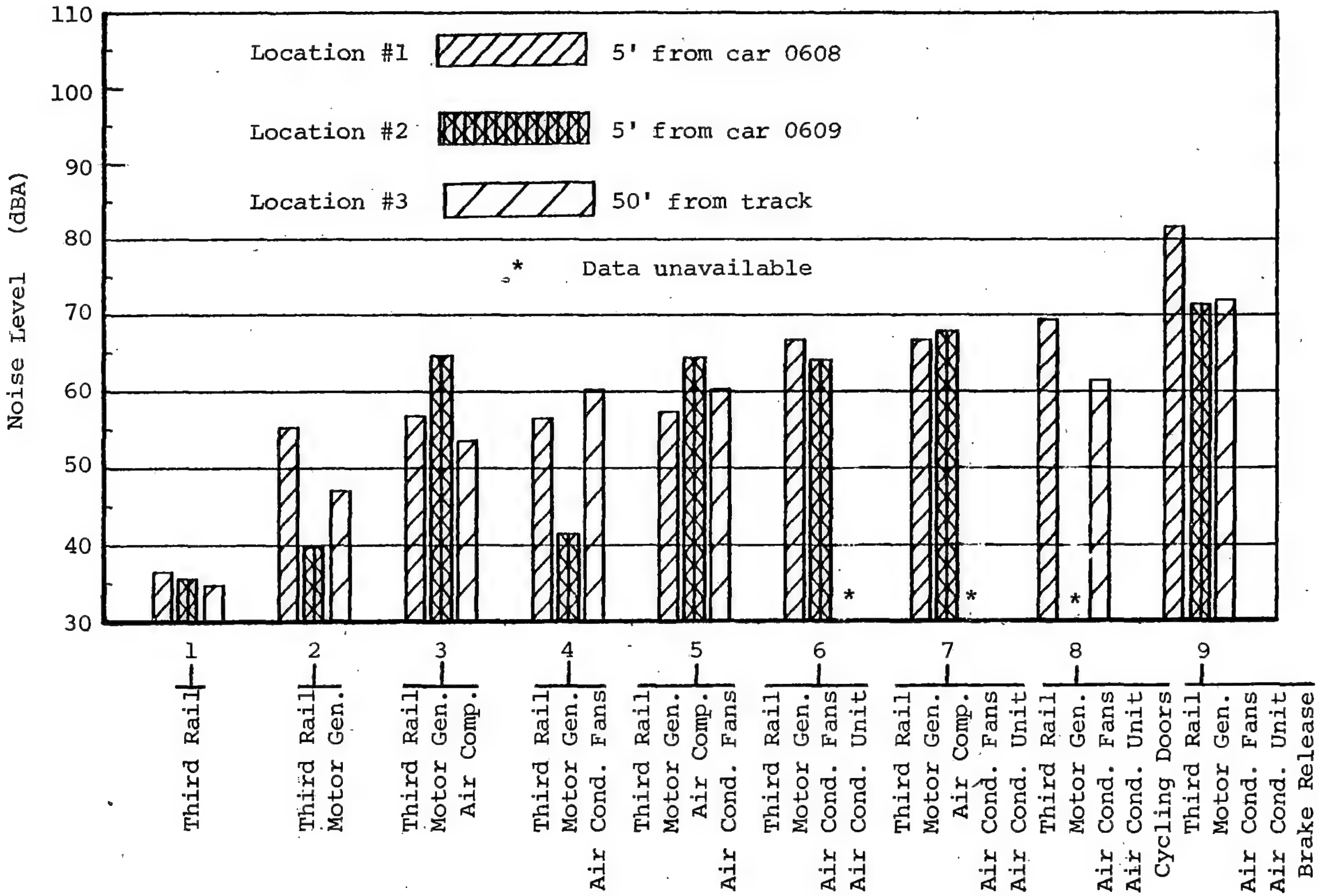


FIGURE 7-1. EQUIPMENT NOISE SURVEY, WAYSIDE.

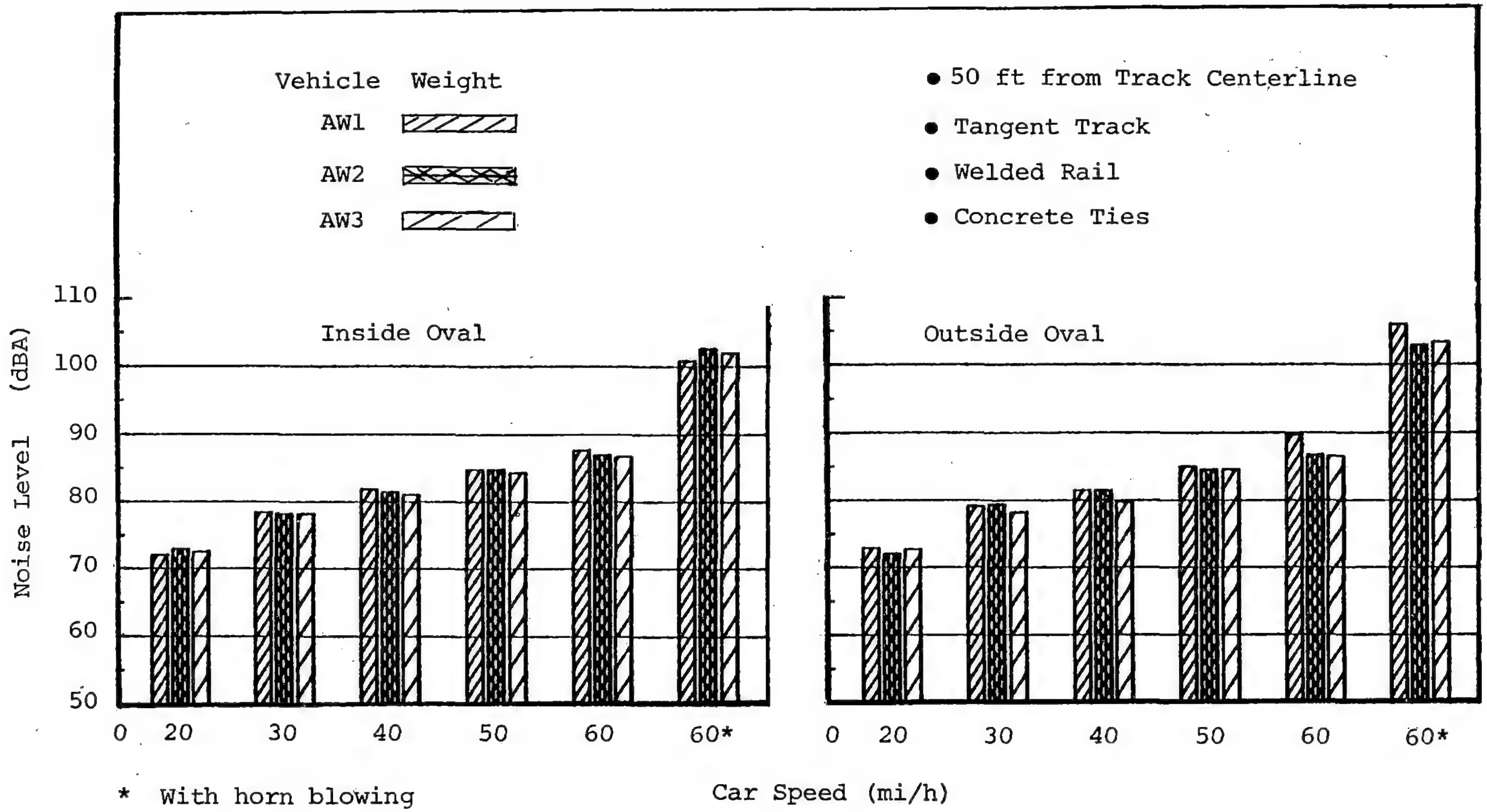


FIGURE 7-2. EFFECT OF SPEED ON WAYSIDE NOISE.

7.2.2 Test Method

a. Noise Measurement. As for the wayside tests, measurements of sound levels were taken using a B&K type 2203 sound level meter. Maximum readings were manually recorded for each test with the instrument set to display A-weighted sound levels (dBA re 2×10^{-5} N/m^2) on a "slow" response setting. The microphone locations used to evaluate the effects of speed, track section, acceleration, and braking are detailed in figure 7-3A; similarly the microphone locations used for the interior noise survey test are shown in figure 7-3B.

b. Test Variables. The following variables were evaluated for interior noise level tests:

- Effect of Speed. Speeds from 10 to 60 mi/h were tested in 10 mi/h increments, on tangent track with welded rail and concrete ties.

- Effect of Track Section. Each section of the TTT was tested (details of the track construction can be found in section 4.1) at a constant speed of 60 mi/h. Measurements were taken at one microphone location (location 7, figure 7-3B), midcar on vehicle 0608 at ear level for a standing passenger.

- Interior Noise Survey. Measurements were taken at sixteen microphone locations as detailed in figure 7-3B, at a constant speed of 40 mi/h between stations 33.0 and 45.0 (welded rail and concrete ties).

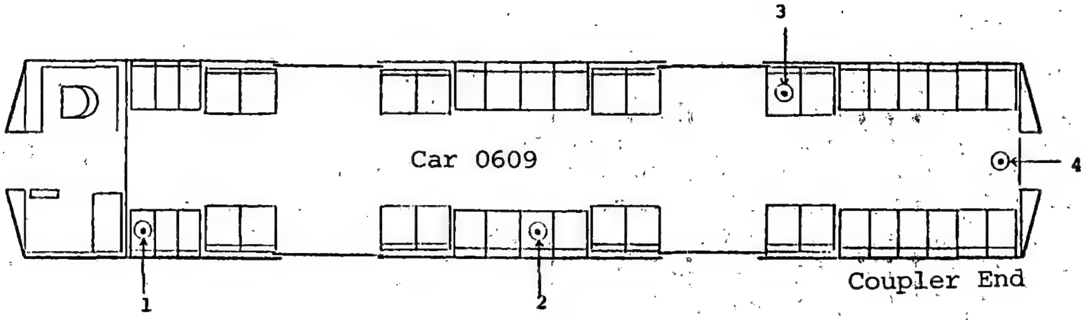
- Effect of Acceleration. Test runs were conducted by accelerating the vehicles from a standing start in each of the four controller positions, P1 through P4. Noise meter readings were monitored as the car accelerated until it achieved a balance speed at each controller position: balance speeds were 15, 25, 35, and 45 mi/h, respectively, and maximum noise meter readings were recorded for each controller setting. The tests were conducted on welded rail with concrete ties, and used four microphone locations in the carbody as illustrated in figure 7-3A.

- Effect of Braking. Tests were conducted using full service blended braking from initial speeds of 15, 25, 35, and 45 mi/h (tangent track with welded rail and conrete ties). Locations of the four acceleration test microphone locations are detailed in figure 7-3A.

All tests were conducted at three vehicle weights, AW1, AW2, and AW3.

7.2.3 Test Results

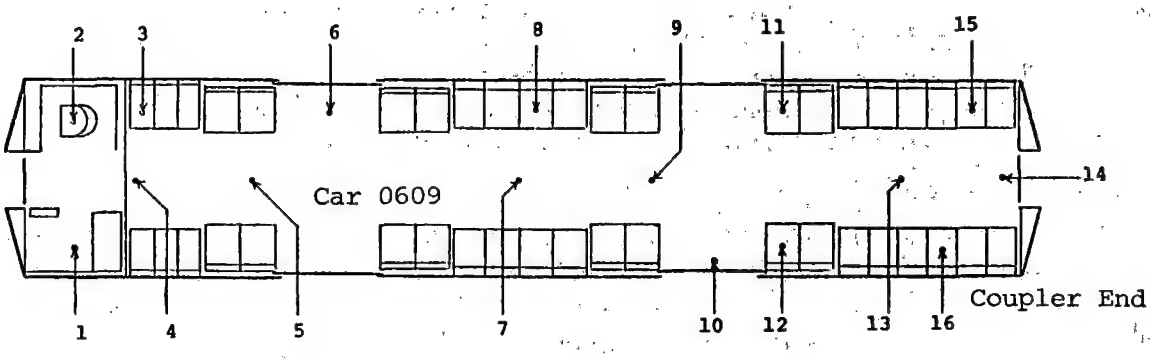
Figures 7-4, 7-5, and 7-6 illustrate the trends of vehicle interior noise levels with speed, over the 10-60 mi/h speed range for each of the weights tested (AW1, AW2, and AW3). The data indicate an increasing noise level with speed from 62-64 dBA at 10 mi/h to 72-76 dBA at 60 mi/h with no significant



1. Sitting-Microphone at ear level
2. Standing-Microphone 5' above floor
3. Sitting-Microphone at ear level
4. Standing-Microphone 5' above floor

Microphone Locations for Effect of Speed, Acceleration and Braking Tests

A.



1. Sitting-Microphone at ear level
2. Sitting-Microphone at ear level
3. Sitting-Microphone at ear level
4. Standing-Microphone 5' above floor
5. Standing-Microphone 5' above floor
6. Standing-Microphone 5' above floor
7. Standing-Microphone 5' above floor
8. Sitting-Microphone at ear level
9. Standing-Microphone 5' above floor
10. Standing-Microphone 5' above floor
11. Sitting-Microphone at ear level
12. Sitting-Microphone at ear level
13. Standing-Microphone 5' above floor
14. Standing-Microphone 5' above floor
15. Sitting-Microphone at ear level
16. Sitting-Microphone at ear level

Microphone Location for Interior Noise Survey

B.

FIGURE 7-3. ONBOARD MICROPHONE LOCATIONS.

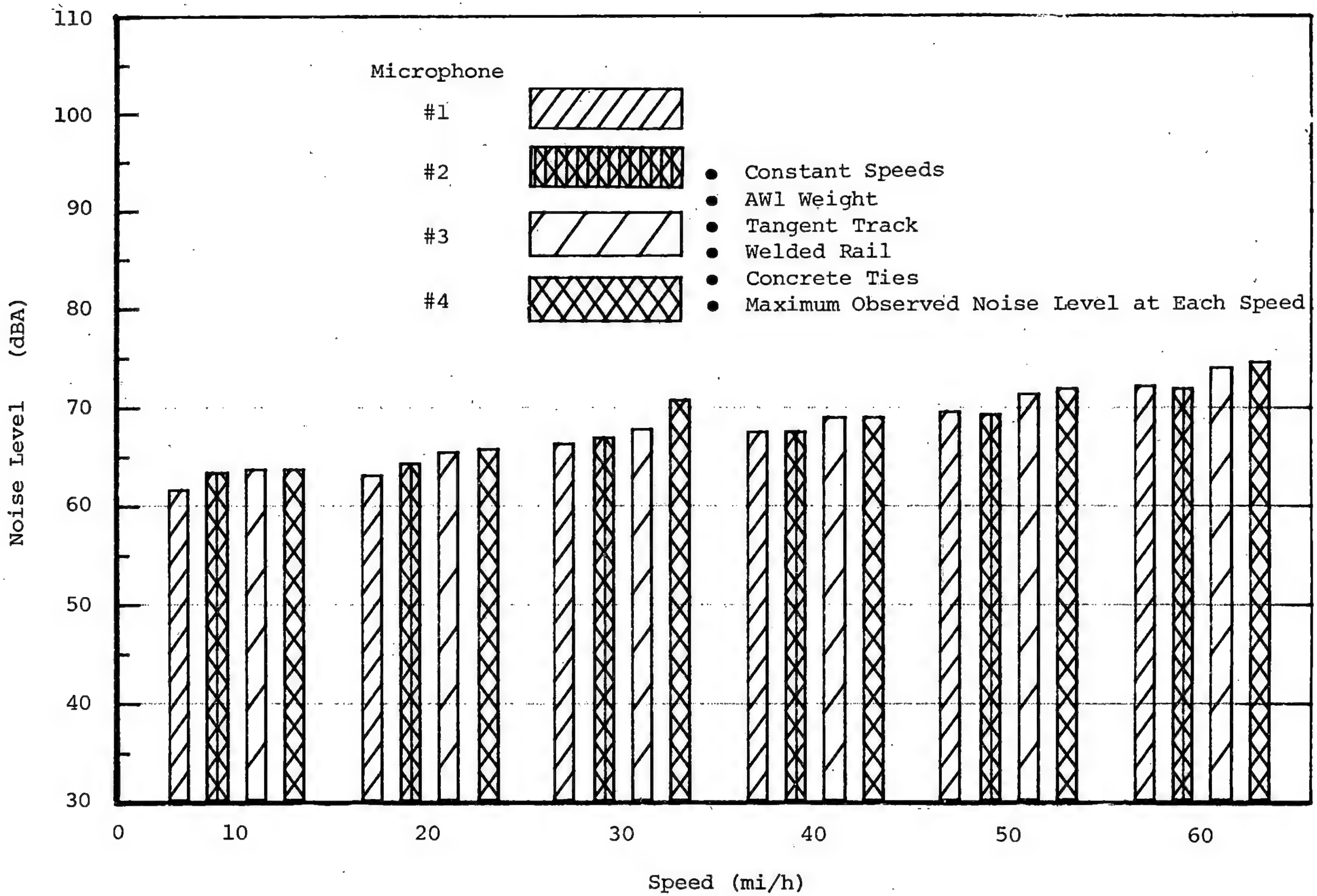


FIGURE 7-4. INTERIOR NOISE VARIATION WITH SPEED, AW1 WEIGHT.

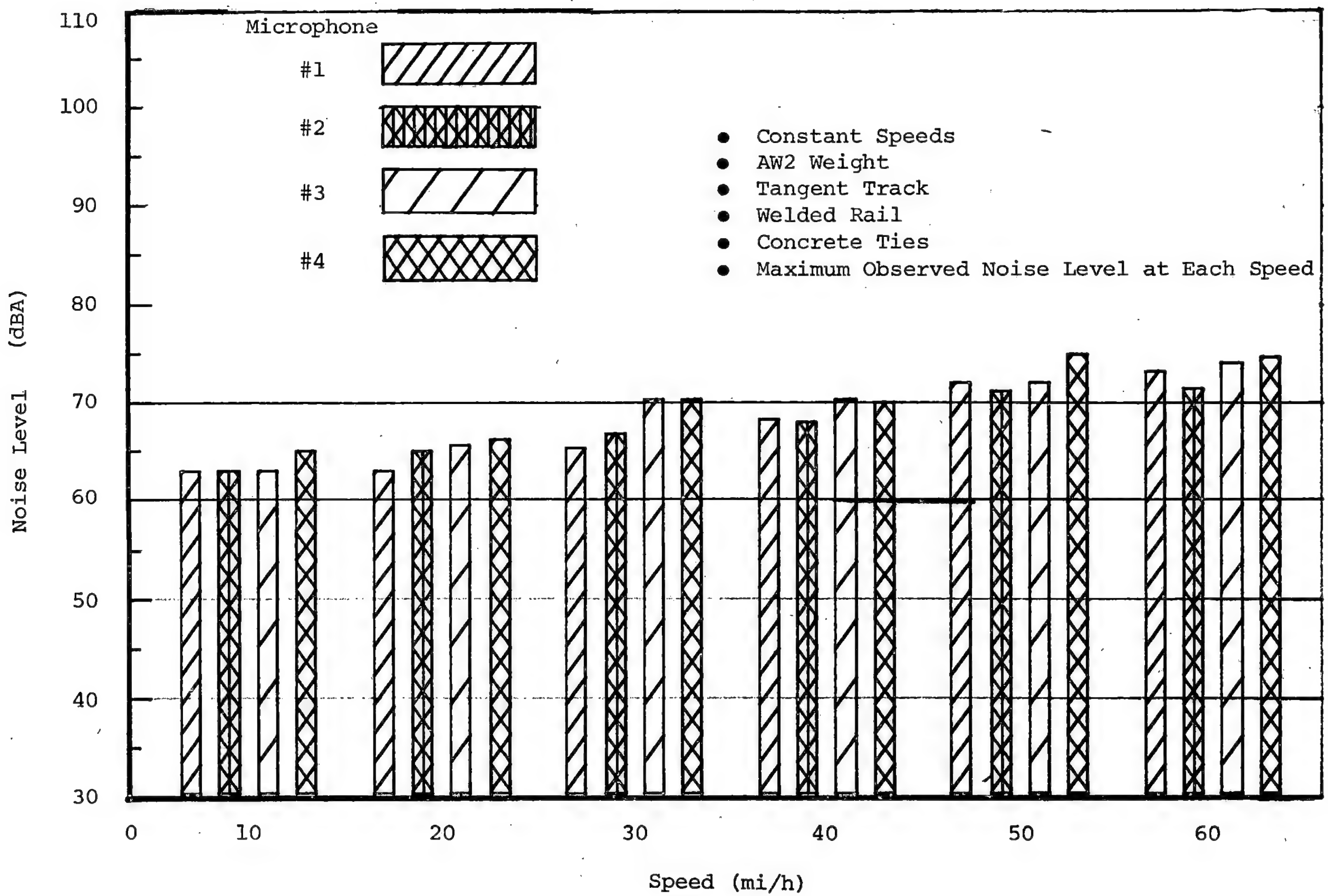


FIGURE 7-5. INTERIOR NOISE VARATION WITH SPEED, AW2 WEIGHT.

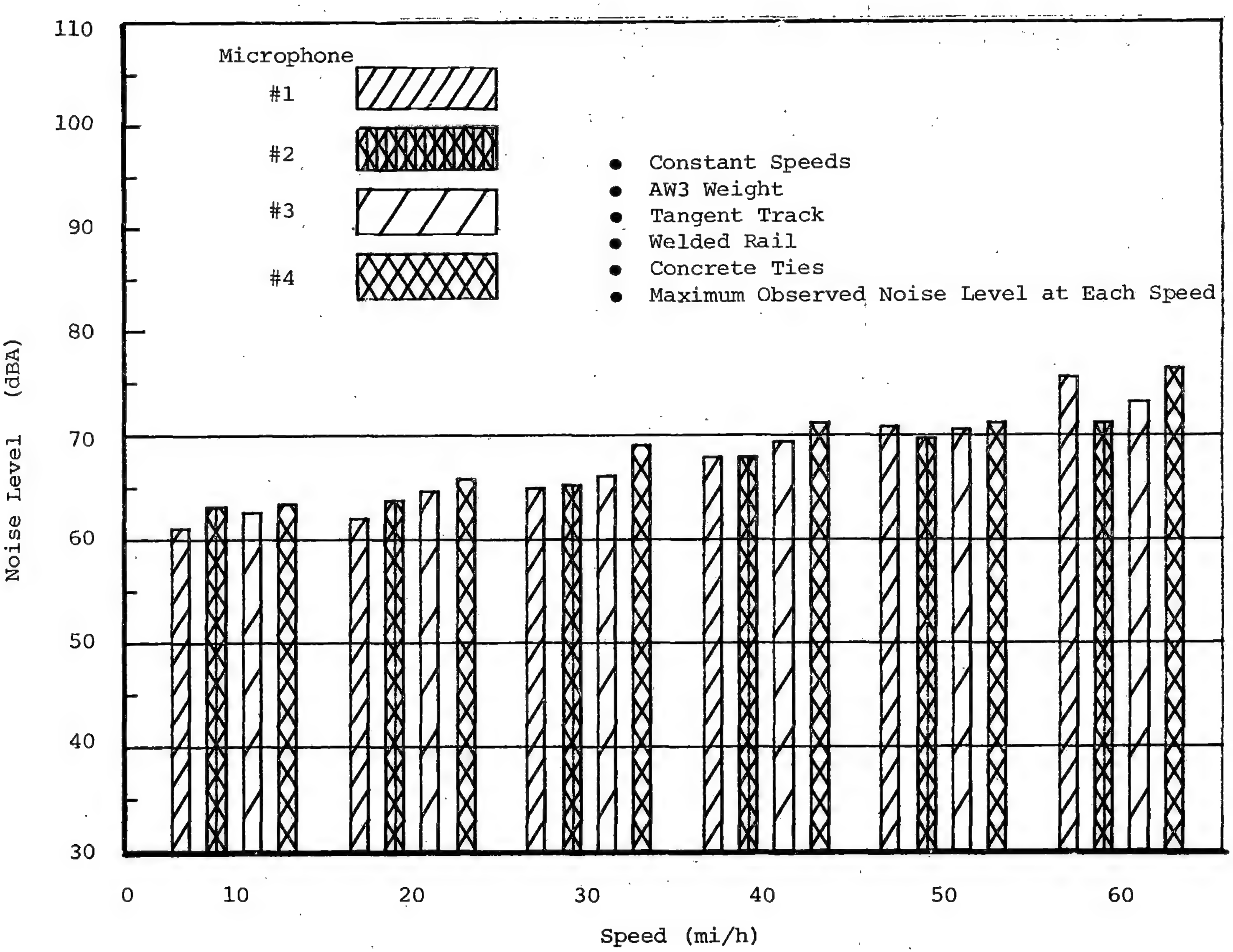


FIGURE 7-6. INTERIOR NOISE VARIATION WITH SPEED, AW3 WEIGHT.

differences in the levels due to car weight. There is a marginal trend in noise levels for different microphone locations, ranking microphone 1 as the lowest level, with microphones 2, 3, and 4 increasing in that order.

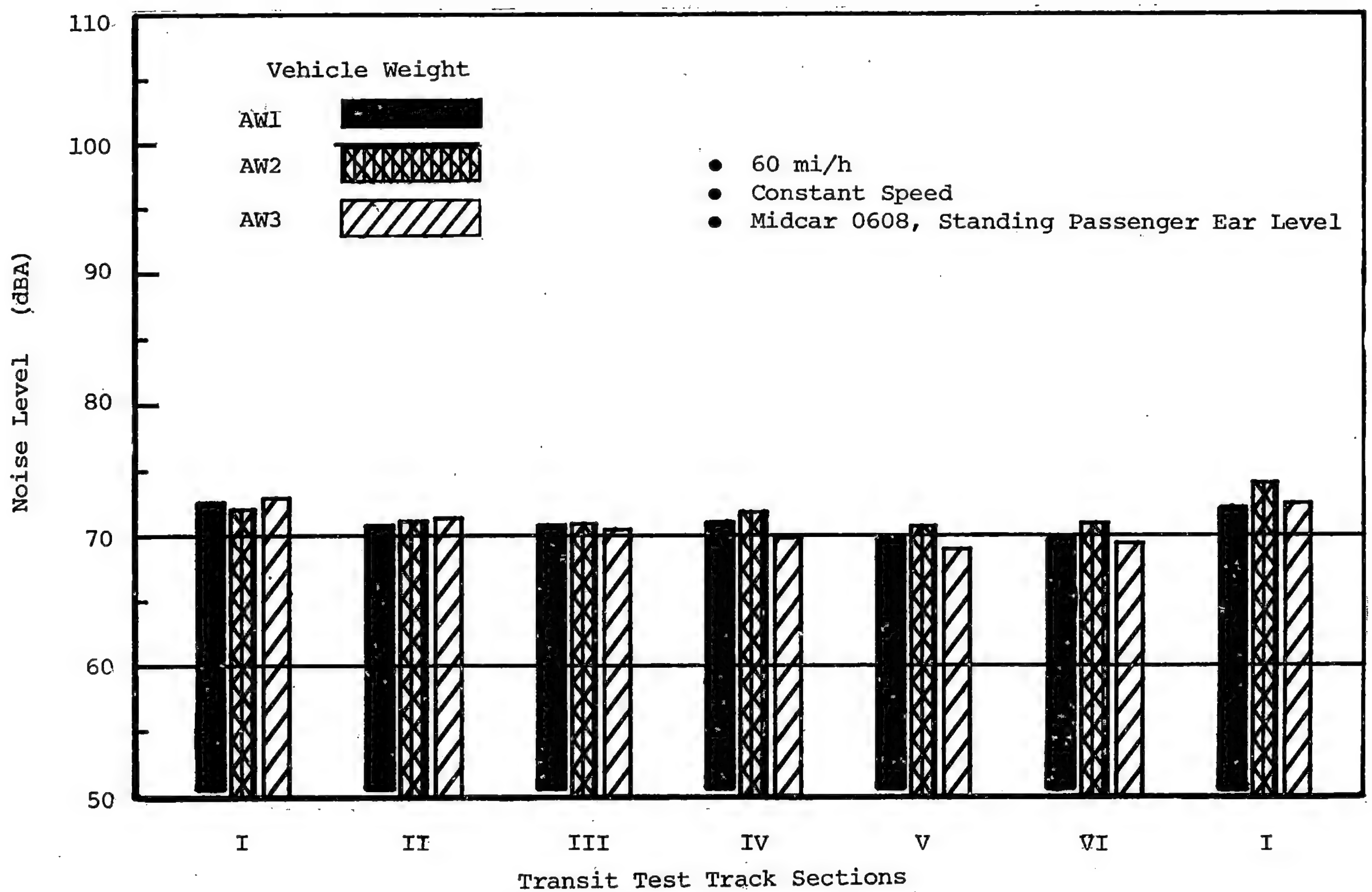
The only criterion for interior noise levels is the specification requirement of 70 dBA for a stationary vehicle. The vehicles also met this requirement at speeds up to 40 mi/h, which is planned operating speed for Blue Line revenue service.

There were no significant trends in interior noise level for the various track sections, the range for the entire TTT oval being less than 5 dBA. The highest levels were recorded over the grade crossing and switch in section I (72-74 dBA); average levels were typically 67-72 dBA. There were no significant differences in sound level for the three vehicle weights tested, as shown by figure 7-7.

Figure 7-8 shows the noise levels at locations throughout the carbody at 40 mi/h on welded rail with concrete ties. Sound levels recorded in the survey ranged from 66 dBA at the midcar seated location to 72 dBA at the coupled end of the car (a standing location, under a ventilator); thus the sound field is reasonably uniform within the vehicle. There were no signficant differences in sound levels at the three vehicle weights.

The data from the acceleration tests (figure 7-9) indicate that higher sound levels occurred for P3 and P4 controller settings (70 and 72 dBA, respectively) than for P1 and P2 settings (64 dBA and 67 dBA, respectively). The sound levels at AW3 car weight were slightly lower than at the lighter weights. Figure 7-10 compares the microphone locations for AW1 weight; little difference in sound level was observed for the four microphone locations. Evaluation of noise level readings for full service braking (figure 7-11) shows a definite trend of higher noise levels with vehicle weight; AW3 was typically 4 dBA higher than AW1, but no trend was observed concerning the initial braking speeds. Figure 7-12 compares the standing and sitting locations at weight AW1; again, no significant difference in sound levels was observed in the four different locations.

In general, interior noise levels in the Blue Line cars in service can be expected to fall in the range 67-72 dBA at speeds up to 40 mi/h over track similar to the TTT.



Track Section Rail Stations	I 12-15	II 21.5-24	III 25.5-28	IV 36-38.5	V 45-48	VI 48-51	I 52-55

FIGURE 7-7. INTERIOR NOISE VARIATION WITH TRACK SECTION.

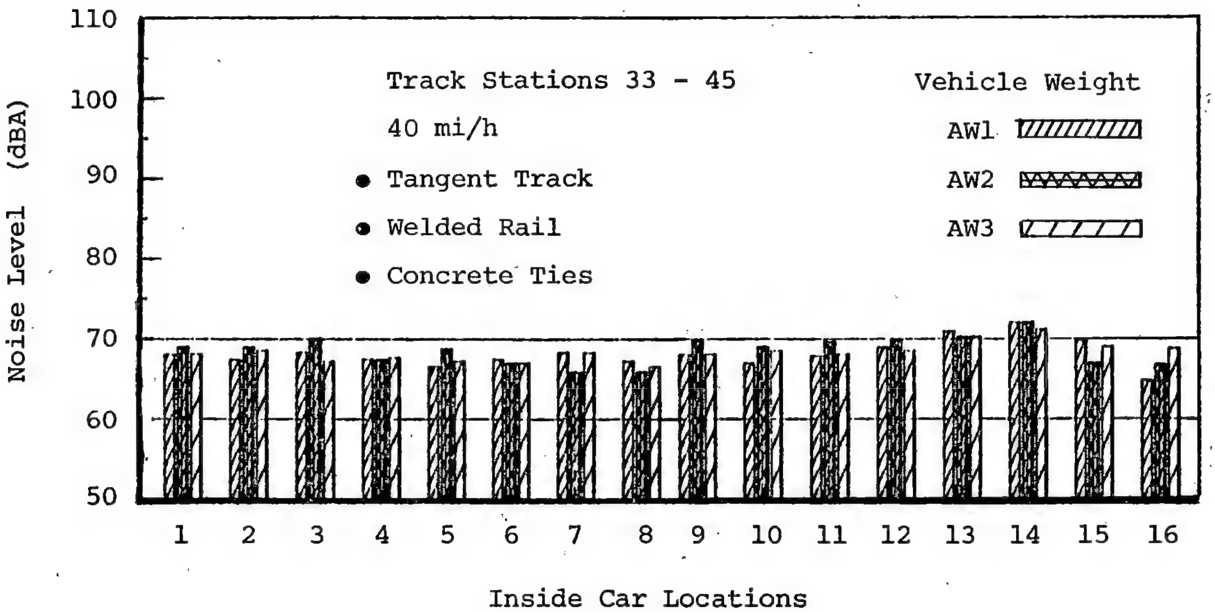


FIGURE 7-8. EFFECT OF INTERIOR LOCATION ON NOISE LEVEL.

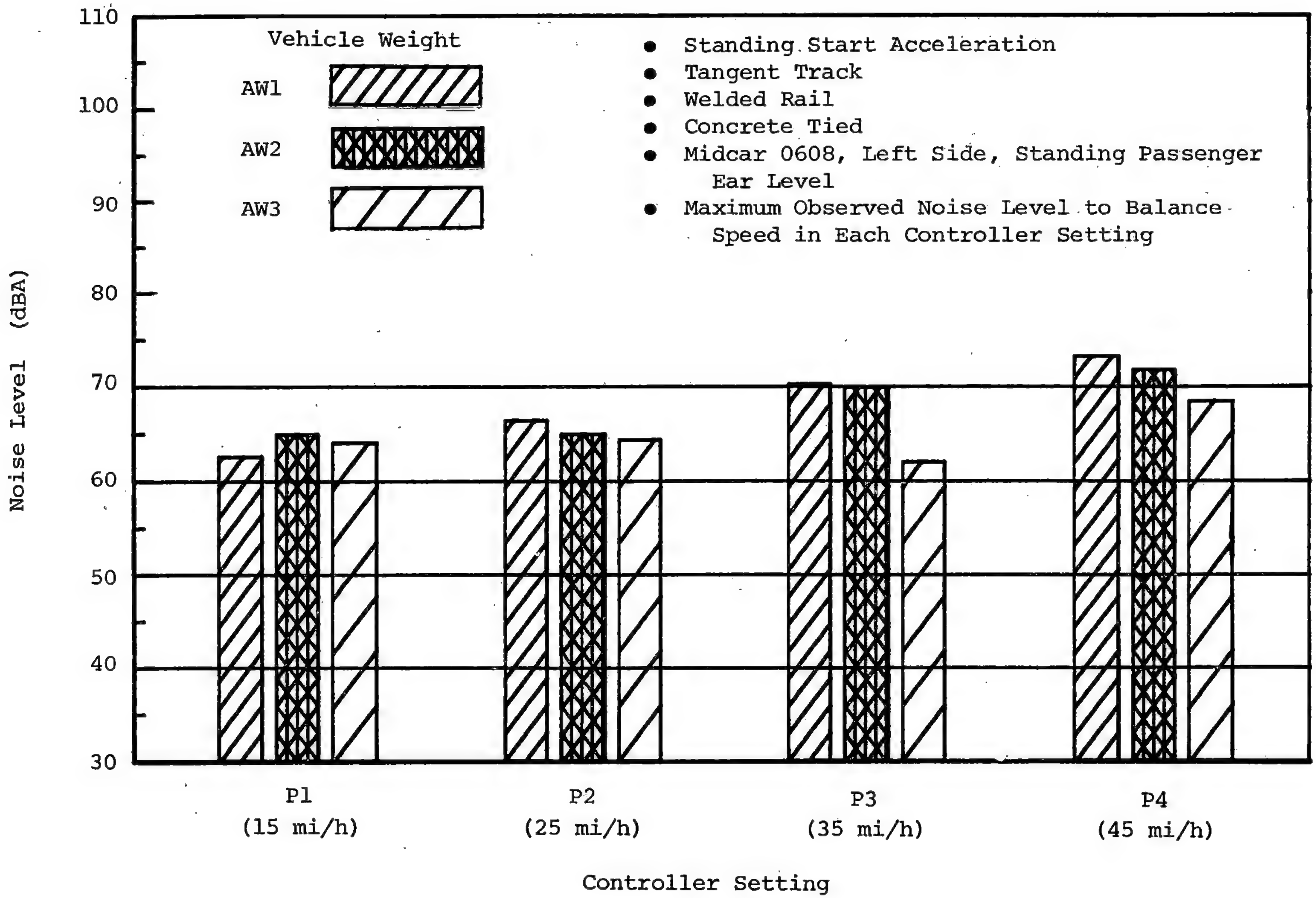


FIGURE 7-9. EFFECT OF ACCELERATION AND WEIGHT ON INTERIOR NOISE.

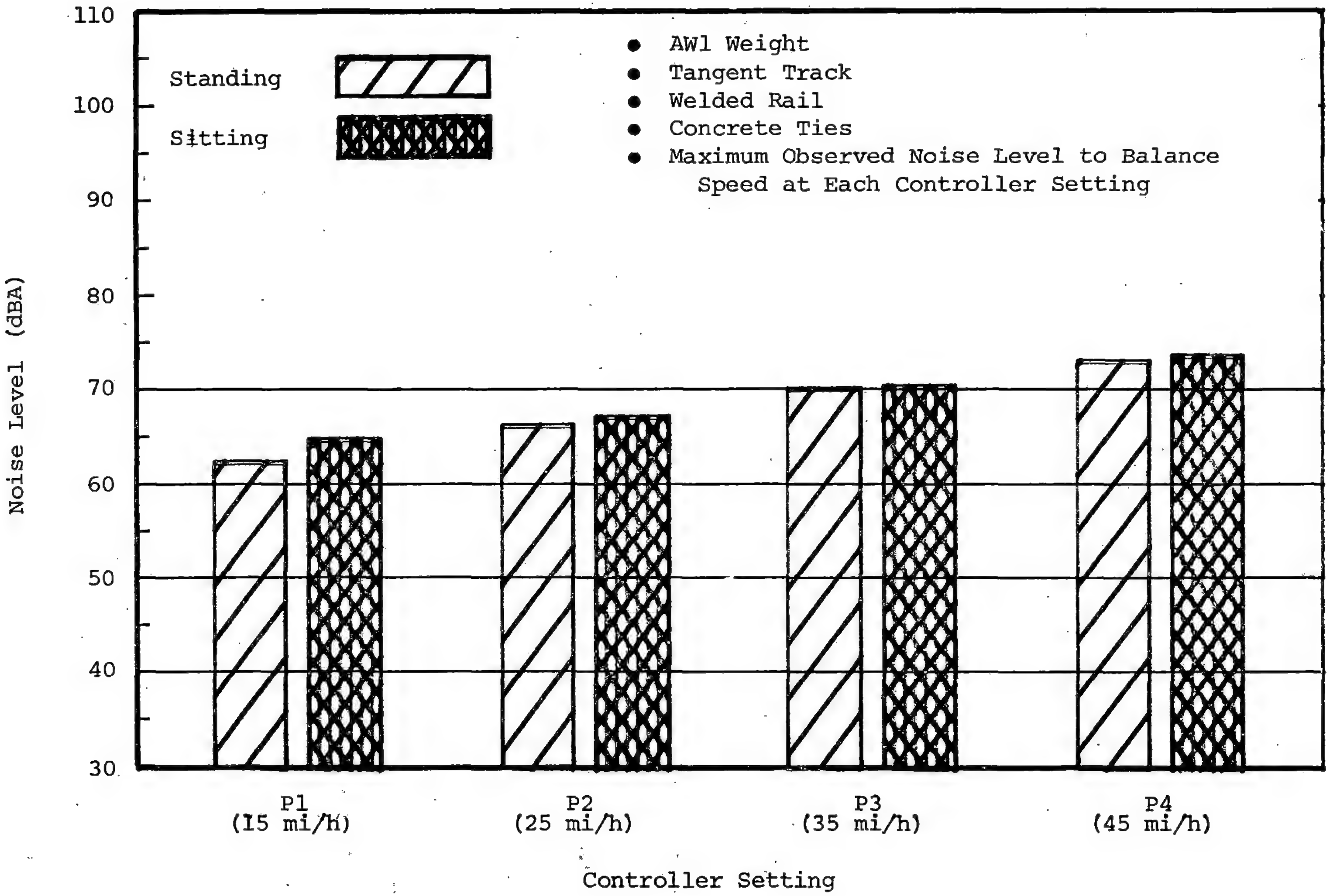


FIGURE 7-10. STANDING AND SITTING NOISE LEVEL COMPARISON UNDER ACCELERATION.

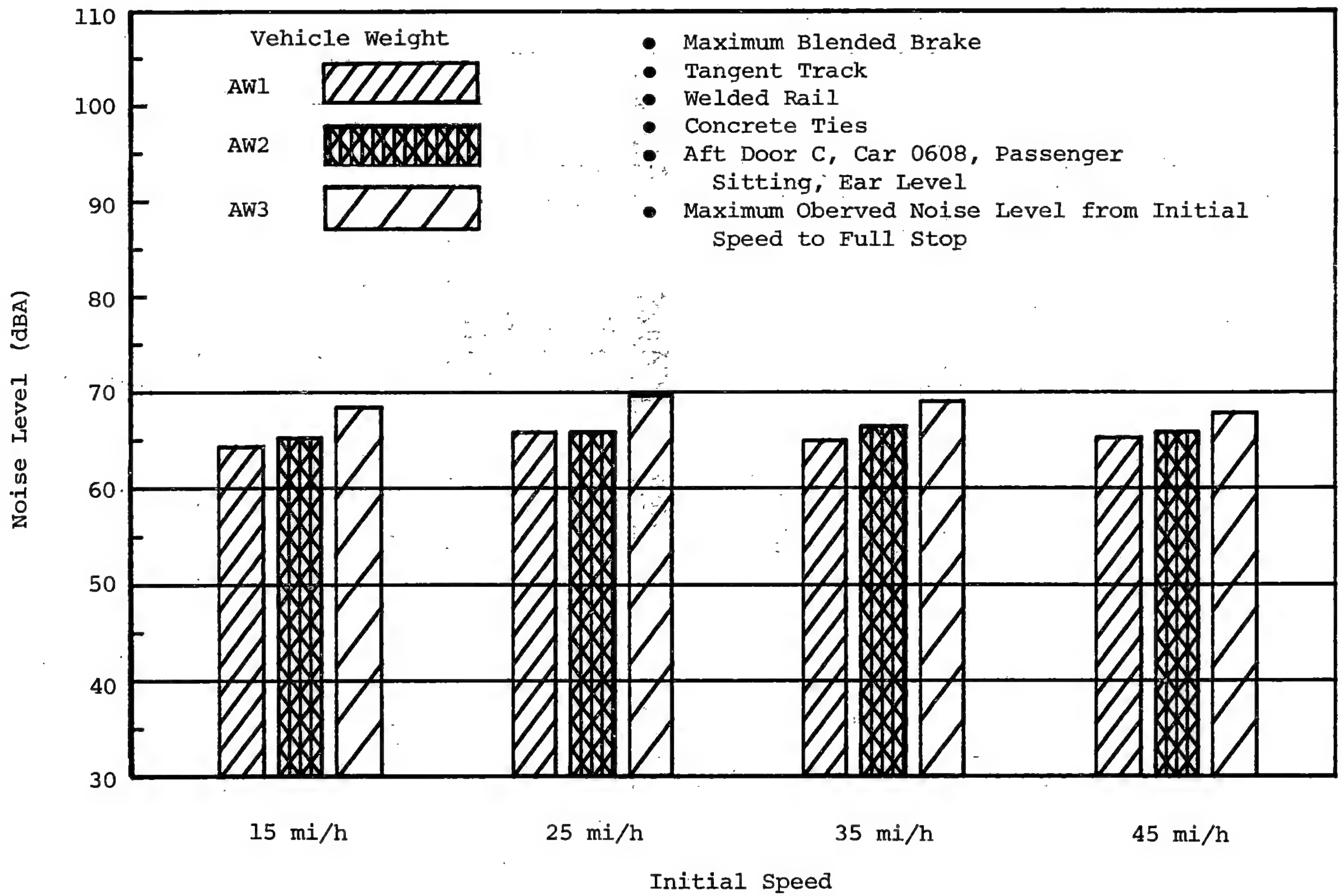


FIGURE 7-11. EFFECT OF WEIGHT ON INTERIOR NOISE, FULL SERVICE BRAKING.

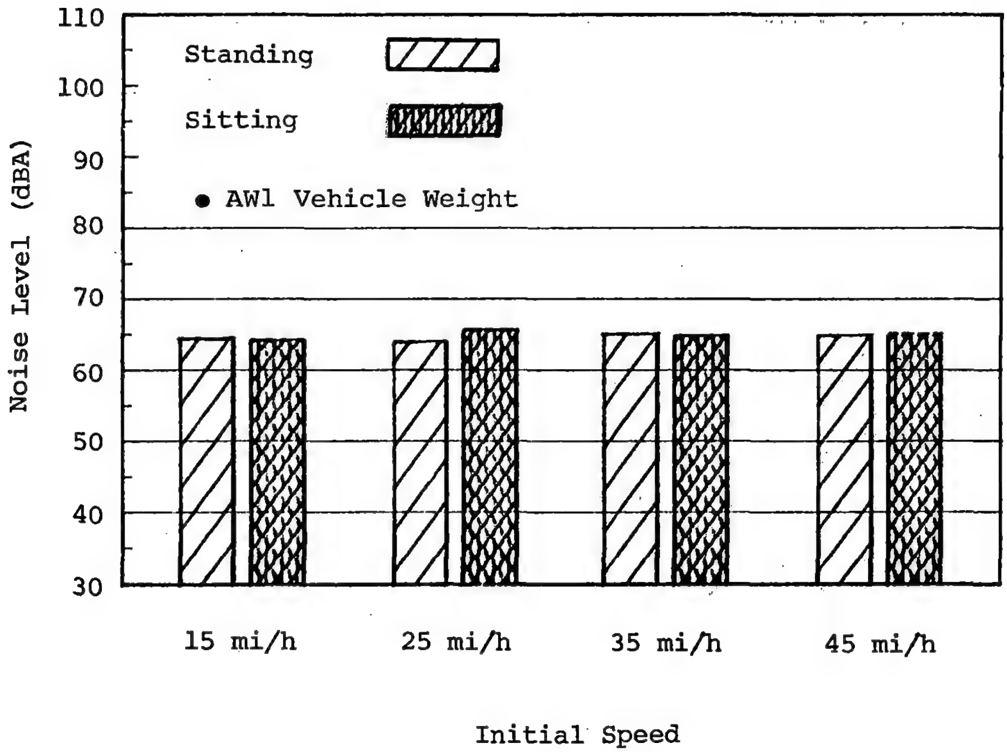


FIGURE 7-12. EFFECT OF BRAKING ON INTERIOR NOISE, STANDING AND SITTING POSITIONS.

Results and Discussion

8.0 RIDE QUALITY TESTS

The purpose of ride quality testing was to determine the vehicle ride characteristics as experienced by a typical passenger and to identify component-induced vibration in the vehicle body. Ride quality testing of the Blue Line cars was conducted in the following areas:

- Component-induced vibration,
- Effect of speed on ride quality,
- Ride quality during vehicle acceleration, and
- Ride quality during vehicle braking.

For the component induced vibration tests, acceleration data were recorded with eight combinations of the vehicle auxiliary equipment operating.

For ride quality testing, acceleration data were recorded while the vehicles were operated at constant speeds from 15 to 60 mi/h on all sections of the TTT, and under acceleration and braking. Identical runs were made at car weights AW1, AW2, and AW3.

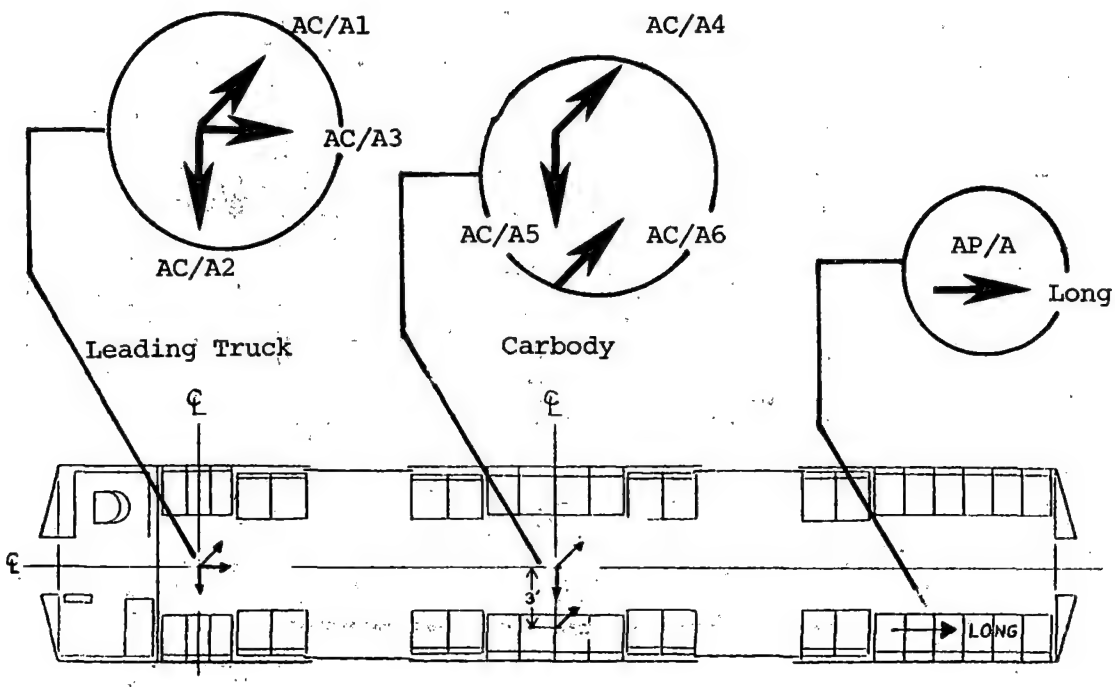
A common instrumentation configuration and data acquisition, processing, and analysis techniques were used for all of the ride quality tests. This methodology is described in the following section before the discussion of the specific tests, in order to avoid unnecessary repetition.

8.1 GENERAL METHODOLOGY

A total of 17 accelerometers were installed on car 0608. Six Servo-type accelerometers were mounted on the carbody (figure 8-1), and three on the axle bearing journal boxes. As a special requirement, eight additional capacitance-type accelerometers were mounted on the truck side frames and the traction motor assembly (figure 8-2). The electrical output of each accelerometer was filtered (table 8-1), monitored on strip charts, and FM-recorded on magnetic tape during the test runs. For each run, a minimum of 30 seconds of the 17-channel vibration data were recorded for analysis.

The recorded data were later digitized at 200 samples per second. Selected channels of these digitized data were processed to obtain engineering unit tabulations and plots in both the time and frequency domains. In the time domain, average, root mean square (rms), and standard deviation values were computed at 1-second time intervals; cumulative values of these parameters were also computed. The cumulative rms value computed about the mean provides a single-figure ride roughness number indicative of the overall run vibration level.

In the frequency domain, power spectral density (PSD), rms amplitude spectra, and 1/3 octave bandwidth spectra were produced using a Fast Fourier Transform digital data processing technique. An rms ride roughness figure was computed from the Fast Fourier data for each of the specified runs. These rms



MBTA Car 0609

Measurement	Standard Output	Measurement No.
1. Fwd Car Floor, Centerline, Vertical	AC/A1	02101
2. Fwd Car Floor, Centerline, Lateral	AC/A2	02102
3. Fwd Car Floor, Centerline, Longitudinal	AC/A3	02103
4. Midcar Floor, Centerline, Vertical	AC/A4	02104
5. Midcar Floor, Centerline, Lateral	AC/A5	02105
6. Midcar Floor, Centerline, Vertical	AC/A6	02106
7. Vehicle Acceleration	AP/A	02001

FIGURE 8-1. CARBODY ACCELEROMETER LOCATIONS.

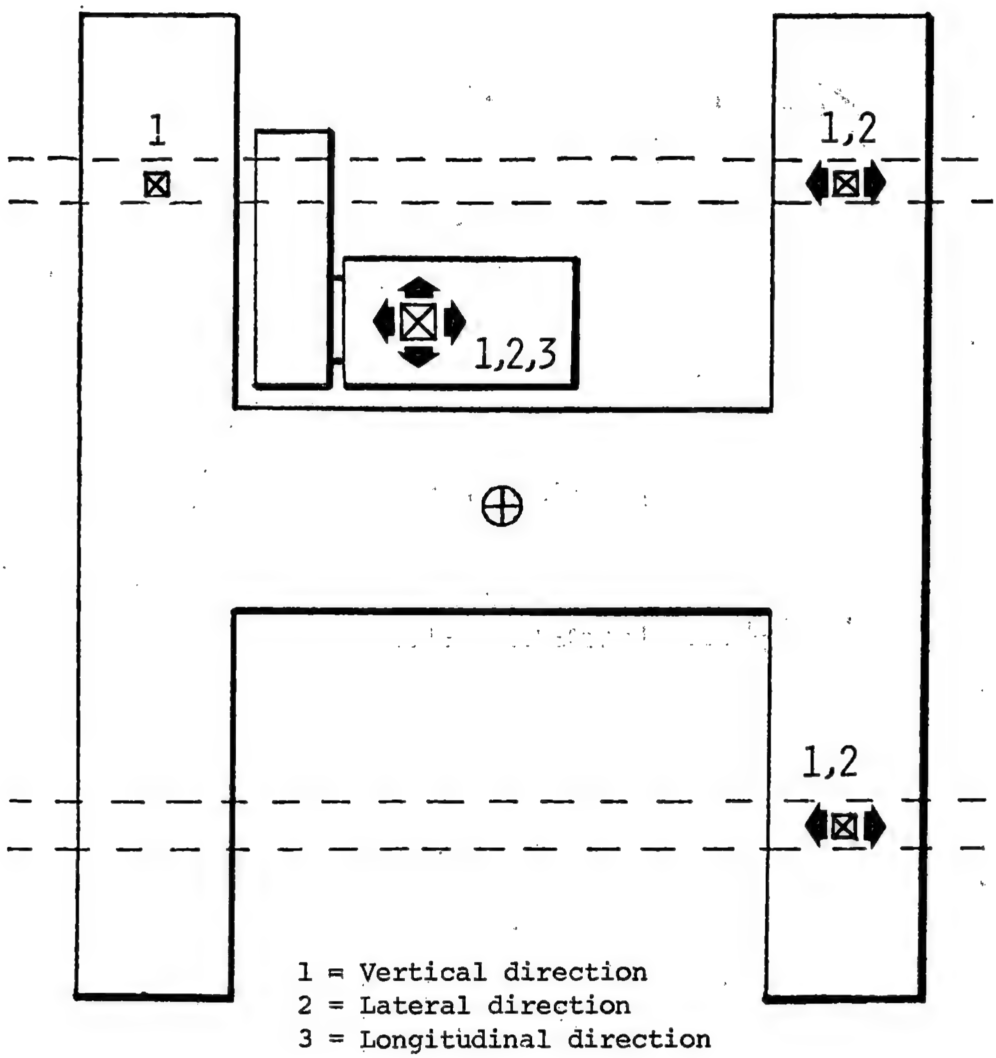


FIGURE 8-2. INSTRUMENTED TRUCK ACCELEROMETER LOCATIONS.

TABLE 8-1. INSTRUMENTATION SENSOR OUTPUT, RIDE QUALITY.

CHANNEL NUMBER	PARAMETER	STANDARD OUTPUT NAME	MEASUREMENT NUMBER	SENSOR TYPE	MEASUREMENT RANGE	FILTER FREQUENCY
1	IRIG "B" TIME	T/A	01411	TIME CODE GENERATOR	-------	1 kHz
2	FWD CAR FLOOR CL VERT	AC/A1	02101	SERVO ACCEL	± 5 g	100 Hz
3	FWD CAR FLOOR CL LAT	AC/A2	02102	SERVO ACCEL	± 0.5 g	100 Hz
4	FWD CAR FLOOR CL LONG	AC/A3	02103	SERVO ACCEL	± 0.5 g	100 Hz
5	MIDCAR FLOOR CL VERT	AC/A4	02104	SERVO ACCEL	± 5 g	100 Hz
6	MIDCAR FLOOR CL LAT	AC/A5	02105	SERVO ACCEL	± 0.5 g	100 Hz
7	MIDCAR FLOOR LEFT VERT	AC/A6	02106	SERVO ACCEL	± 5 g	100 Hz
8	LEAD AXLE RIGHT JOURNAL VERT	AJ/A1	02201	PIEZO ACCEL	± 30 g	1 kHz
9	LEAD AXLE RIGHT JOURNAL LAT	AJ/A2	02202	PIEZO ACCEL	± 10 g	1 KHz
10	LEAD AXLE LEFT JOURNAL VERT	AJ/A3	02203	PIEZO ACCEL	± 30 g	1 kHz
11	SIDE FRAME FRONT LEFT VERT	SFFLV	02204	CAPACITANCE ACCEL	± 5 g	300 Hz
12	TRACTION MOTOR VERT	TMV	02209	PIEZO ACCEL	± 10 g	300 Hz
13	TRACTION MOTOR LAT	TML	02210	PIEZO ACCEL	± 10 g	300 Hz
14	TRACTION MOTOR LONG	TMLO	02211	PIEZO ACCEL	± 10 g	300 Hz
15	SIDE FRAME FRONT RIGHT VERT	SFFRV	02205	CAPACITANCE ACCEL	± 5 g	300 Hz
16	SIDE FRAME FRONT RIGHT LAT	SFFRL	02206	CAPACITANCE ACCEL	± 5 g	300 Hz
17	SIDE FRAME REAR RIGHT VERT	SFRRV	02207	CAPACITANCE ACCEL	± 5 g	300 Hz
18	SIDE FRAME REAR RIGHT LAT	SFRRL	02208	CAPACITANCE ACCEL	± 5 g	300 Hz

figures were computed as straight rms values and also were frequency-weighted for human sensitivity according to the International Standards Organization (ISO) weighting curves shown in figure 8-3, using digital filtering techniques.

The rms vibration figures indicate the overall vibration levels encountered on the vehicle. The dependence of vibration on car weight, speed, acceleration, deceleration, and track construction is illustrated in cross-plot figures and comparative histograms, presented in the test results section. PSD plots are also included in each test section for frequency domain comparisons.

A subset of the complete test matrix was chosen for evaluation, in order to limit the required analysis to a manageable level. This subset was selected to provide enough representative cross sections to define the specific test objectives. Three carbody accelerometers were assessed: forward car centerline vertical, forward car centerline lateral, and the midcar centerline vertical accelerations. In all sections of the analysis, the figures and graphs presented are only a sample of the actual number of runs and measurements considered.

Carbody accelerometers were mounted on fixtures positioned on the car floor, weighted down to overcome the resilience of the carpet, and levelled. Prior to the test runs, an impulse (shock) test was conducted and the natural frequencies of the accelerometer fixtures were observed. The results of this test are presented in table 8-2.

TABLE 8-2. CAR FLOOR ACCELEROMETER FIXTURE RESONANCE.

Fixture Location	Resonant Frequency (Hz)		
	Vertical	Lateral	Longitudinal
Forward Car Centerline	95	95	80
Midcar Centerline	70	50	--
Midcar Left	70	--	--

Vibration from these tests was not recorded for spectral analysis; thus the figures represent approximate values obtained from the time history charts. They indicate that some fixture resonance phenomena may be observed at the midcar measurements where resonance lies in the 50 to 70 Hz region. Very little vibration was observed in the forward car vertical measurement, and the vibration that was observed at this location exhibited frequencies sufficiently high to preclude most carbody vibration interaction.

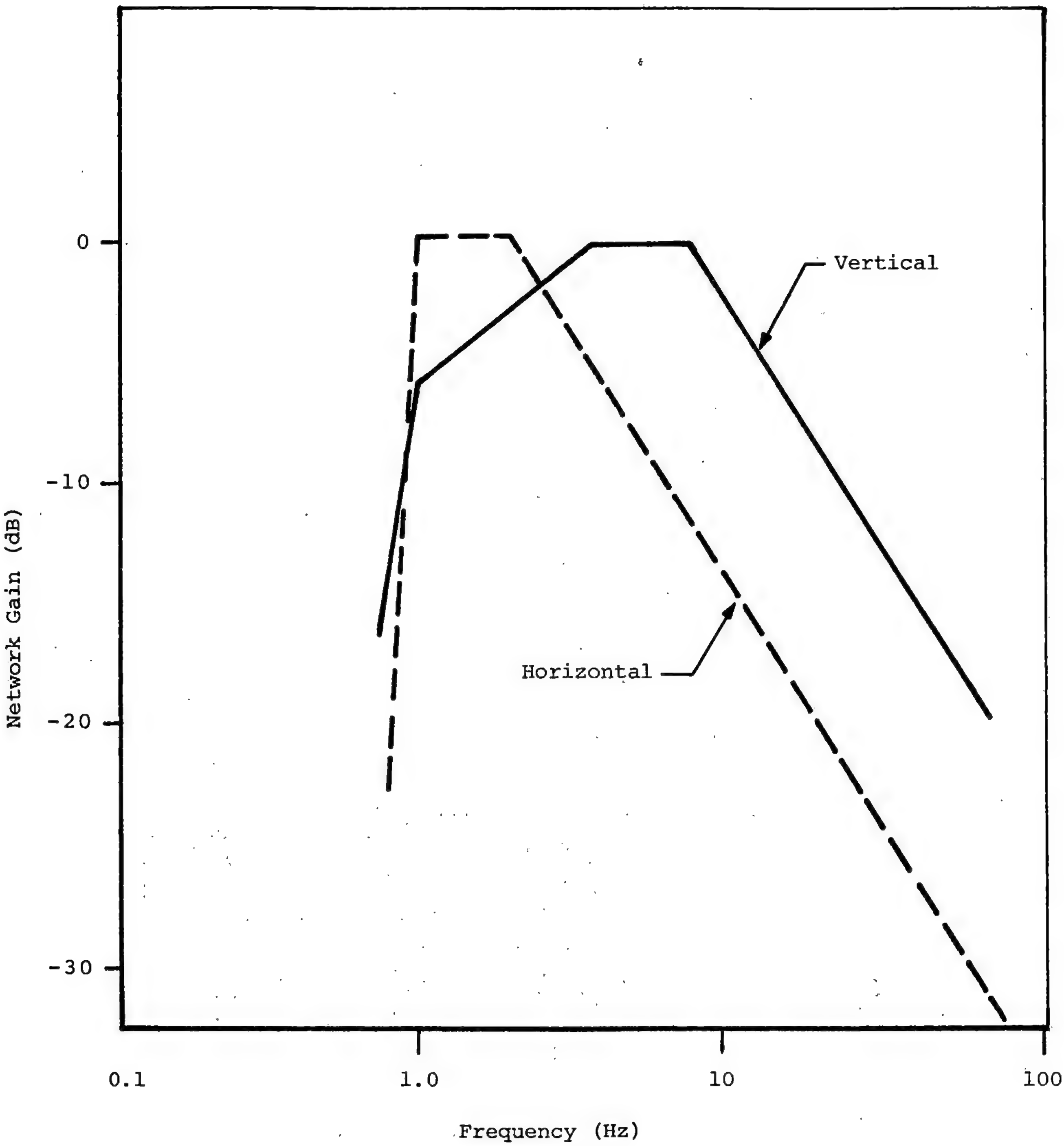


FIGURE 8-3. ISO WEIGHTING CURVES.

8.2 COMPONENT-INDUCED VIBRATION

8.2.1 Test Objective

To determine vibration levels of the carbody arising from operation of the test vehicle's auxiliary equipment.

8.2.2 Test Method

Vibration measurements were recorded while the vehicle was stationary on a level section of the TTT. Eight combinations of auxiliary equipment were tested, representing cumulative vibrational contributions of the individual auxiliary components. Tests evaluated the vibration due to the motor generator set, the air compressor, the evaporator fans, the air conditioning, door cycling, and brake application.

8.2.3 Test Results

Three of the six carbody measurements were evaluated; they were the vertical and lateral accelerometers located on the car floor centerline directly over the truck bolster (uncoupled end), and a second vertical measurement at the midcar centerline floor location. Outputs of these accelerometers were low-pass filtered at 100 Hz. A sample time trace of each of these outputs is presented in figure 8-4.

Spectral content of the vertical induced vibration, the principal mode of component-induced vibration, may be observed in the PSD plots of figure 8-5. These plots were generated by Fast Fourier digital data processing, ensemble-averaged to include approximately 25 seconds of data. All the spectral plots display very little vibration (less than 0.01 g rms) induced by the car equipment; the salient exception is the trainline air compressor, which is located forward beneath the vehicle floor. Overall rms vertical vibration levels as high as 0.024 g unweighted and 0.013 g weighted were recorded. Although these vibrations were noticeable, they fall well below the levels considered to cause any human discomfort.

The PSD's of vertical vibration at midcar and forward car locations indicate a general energy content near 0.6 Hz. This content was typical for all runs irrespective of equipment cycling. Amplitude and frequency of this vibration suggest a fundamental carbody suspension mode (possibly lower sway). The same content, reduced by a factor of 10, could be observed in the lateral vibrations. None of the peaks in these PSD's can be attributed to the motor generator unit.

Vibration from the most significant contributor, the trainline air compressor, can be seen to have components near 50 Hz and 72 Hz (figure 8-5); these are more easily seen in the lateral measurements. Evaporator fans contribute slight vibrations at 30 Hz, while the air conditioner unit provides a similar contribution near 28 Hz. Door cycling appears to contribute some 40 Hz lateral vibration and possibly stimulates the 10 Hz resonance that is barely observable in the other traces. Brake application does not contribute appreciably to the vibrational environment.

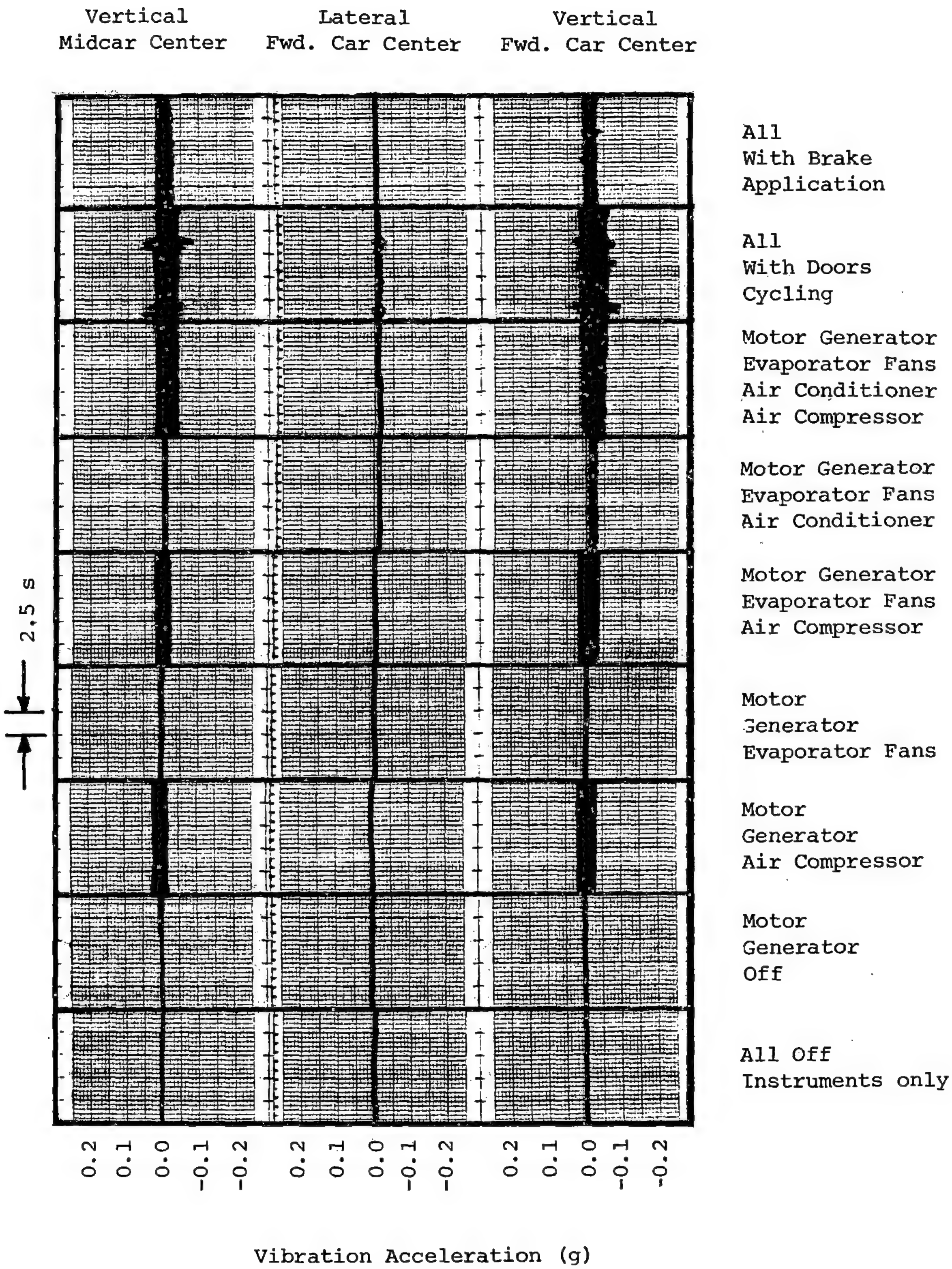


FIGURE 8-4. SAMPLE TIME HISTORY TRACE OF COMPONENT-INDUCED VIBRATION.

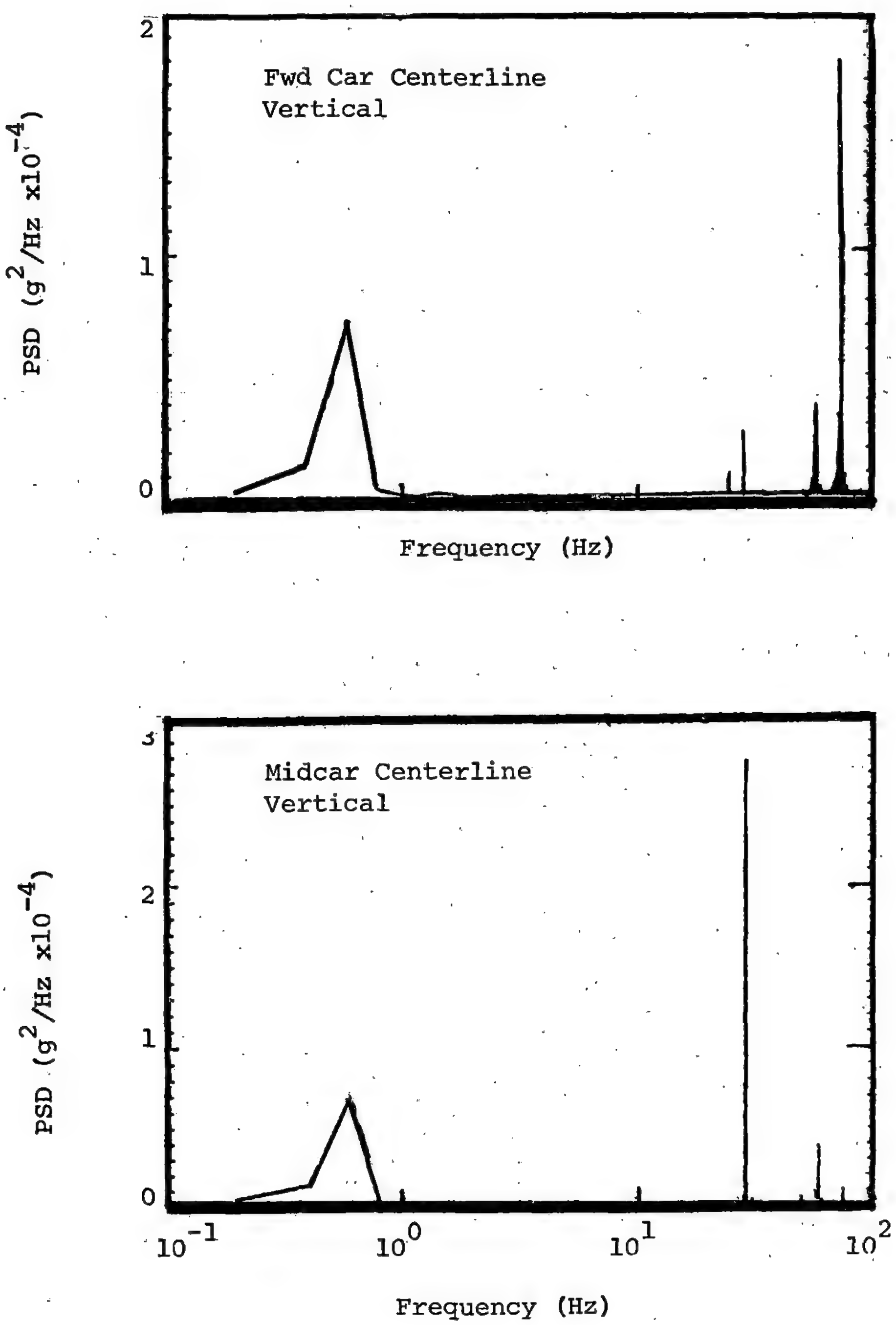


FIGURE 8-5. COMPONENT-INDUCED VIBRATION SPECTRA.

Figure 8-6 summarizes the (unweighted) vertical and lateral vibration amplitudes induced by component groups at the forward car centerline position and at the midcar position. Overall rms levels were calculated from the total area under the PSD curves from 0-80 Hz; rms figures were computed from PSD's, both weighted and unweighted for human sensitivity.[1] Figure 8-7 depicts the weighted vibration components. It is apparent from these charts that the major vibration is contributed in the vertical direction. Test runs exhibiting the highest vibration values were those in which the air compressor was operating.

8.3 EFFECT OF SPEED ON RIDE QUALITY

8.3.1 Test Objective

To determine the maximum vibration values encountered due to vehicle motion at constant speed on the TTT.

8.3.2 Test Method

Vibration measurements were recorded at selected speeds of 15, 30, 45, and 60 mi/h on all sections of the test track, including the north gap and switch in track section I. The test matrix was repeated for vehicle weights of AW1, AW2, and AW3. Lead weights were distributed on the car floor to simulate passenger lading.

8.3.3 Test Results

The rms and weighted rms values were computed over the frequency range of 0 to 80 Hz as an overall indication of the vibration conditions induced at each speed. These "ride roughness" rms numbers are plotted at each test speed in figures 8-8 and 8-9 for the forward car vertical and lateral measurements, and the midcar vertical measurements. Values for car weights AW1 and AW3 are shown for comparison. The graphs indicate that the highest vibrations are observed at the midcar location in the vertical direction. Generally, vibration increased with speed, although the midcar vertical measurement at car weight AW3 peaks near 45 mi/h.

a. Effects of car weight. There is a vibrational increment due to vehicle weight, with the AW1 weight rms accelerations showing a consistent, but minor, trend to higher values (figures 8-8 and 8-9). This may be brought about by ballasting the vehicle with lead ingots, which could have provided additional damping to the car floor, or detuned the transmissibility of the body structure.

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[1] Guide for the Evaluation of Human Exposure to Whole-Body Vibration, ISO.2631-1978 (E) TC-108.

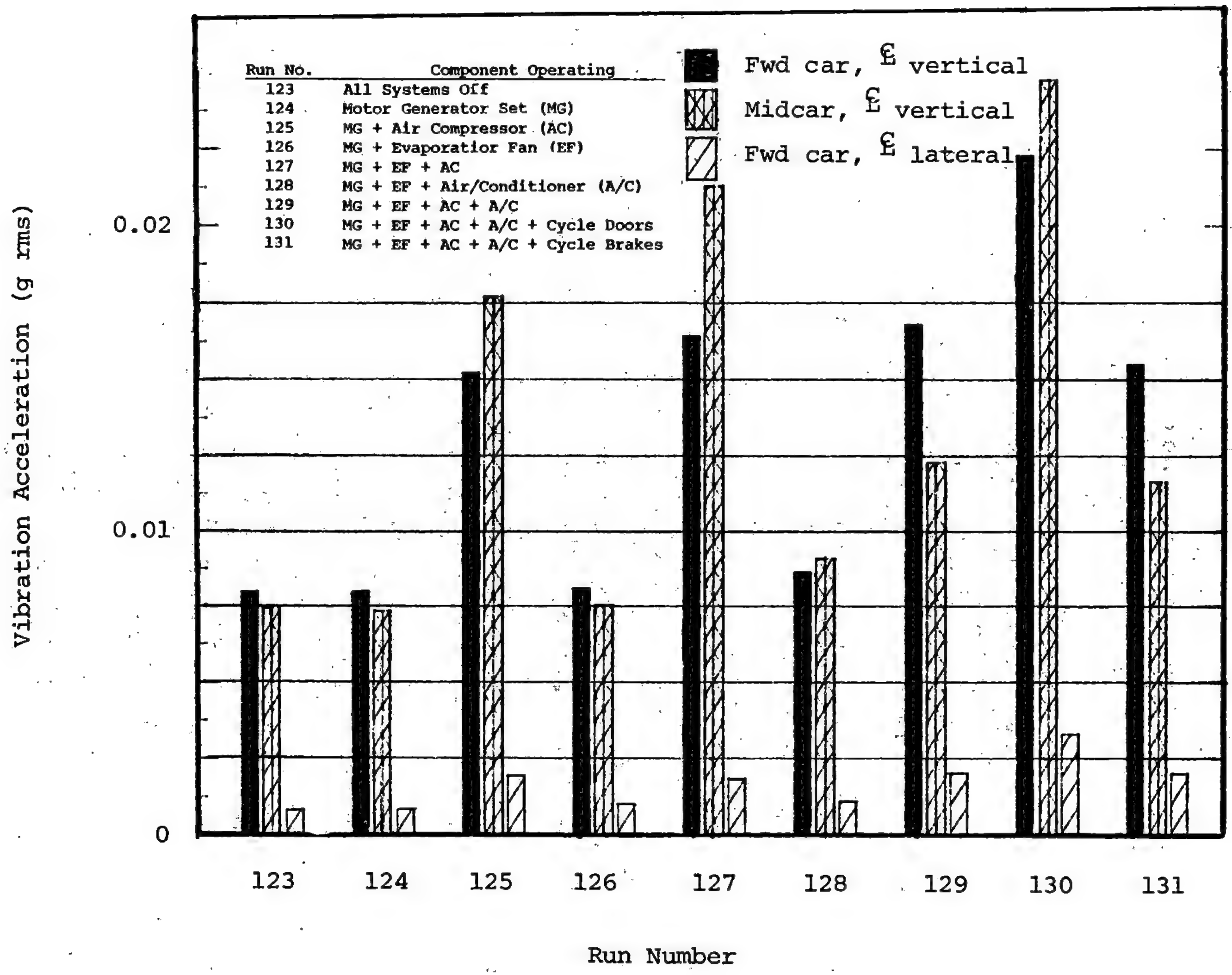

FIGURE 8-6. COMPONENT-INDUCED VIBRATION, UNWEIGHTED RMS.

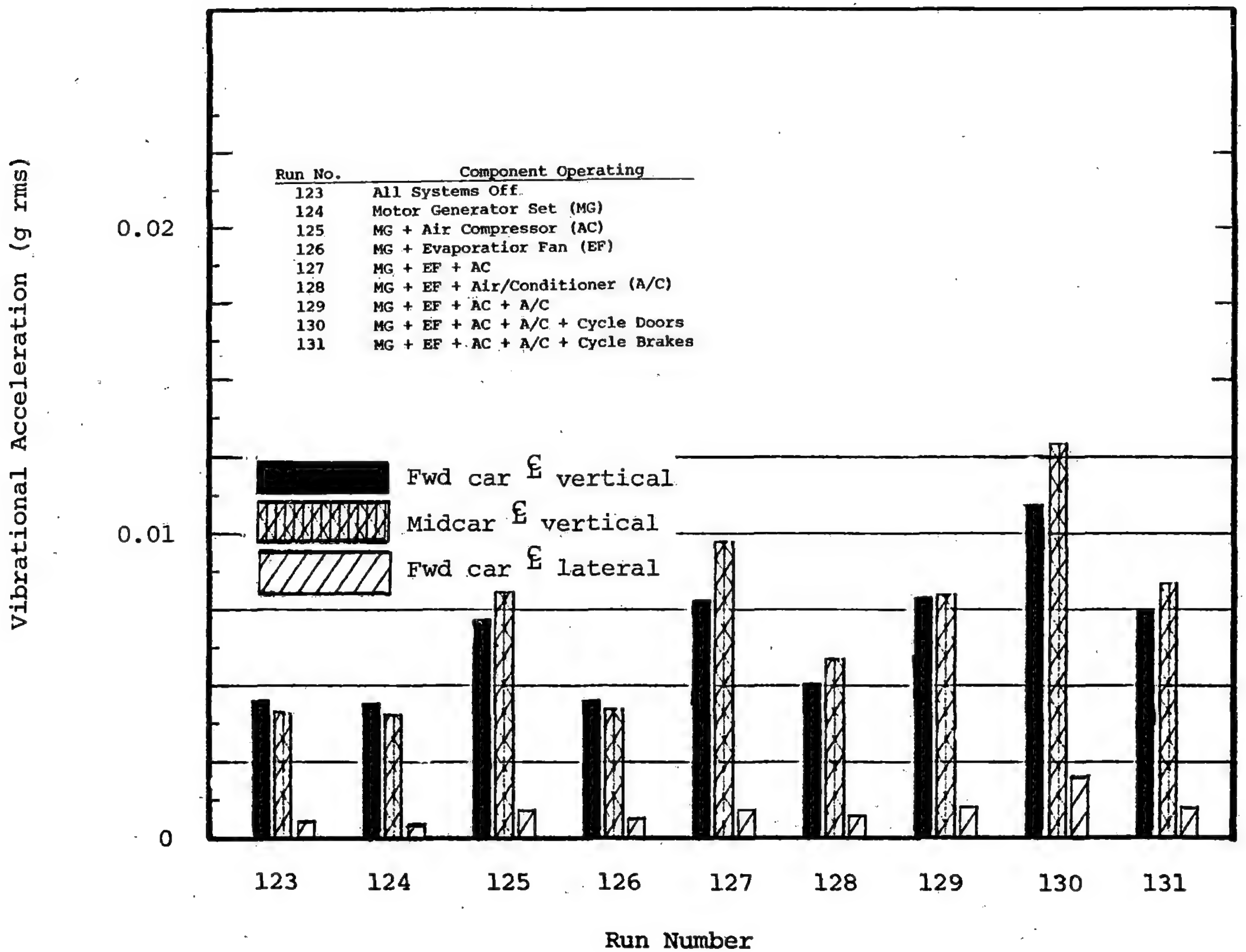

FIGURE 8-7. COMPONENT-INDUCED VIBRATION, WEIGHTED RMS.

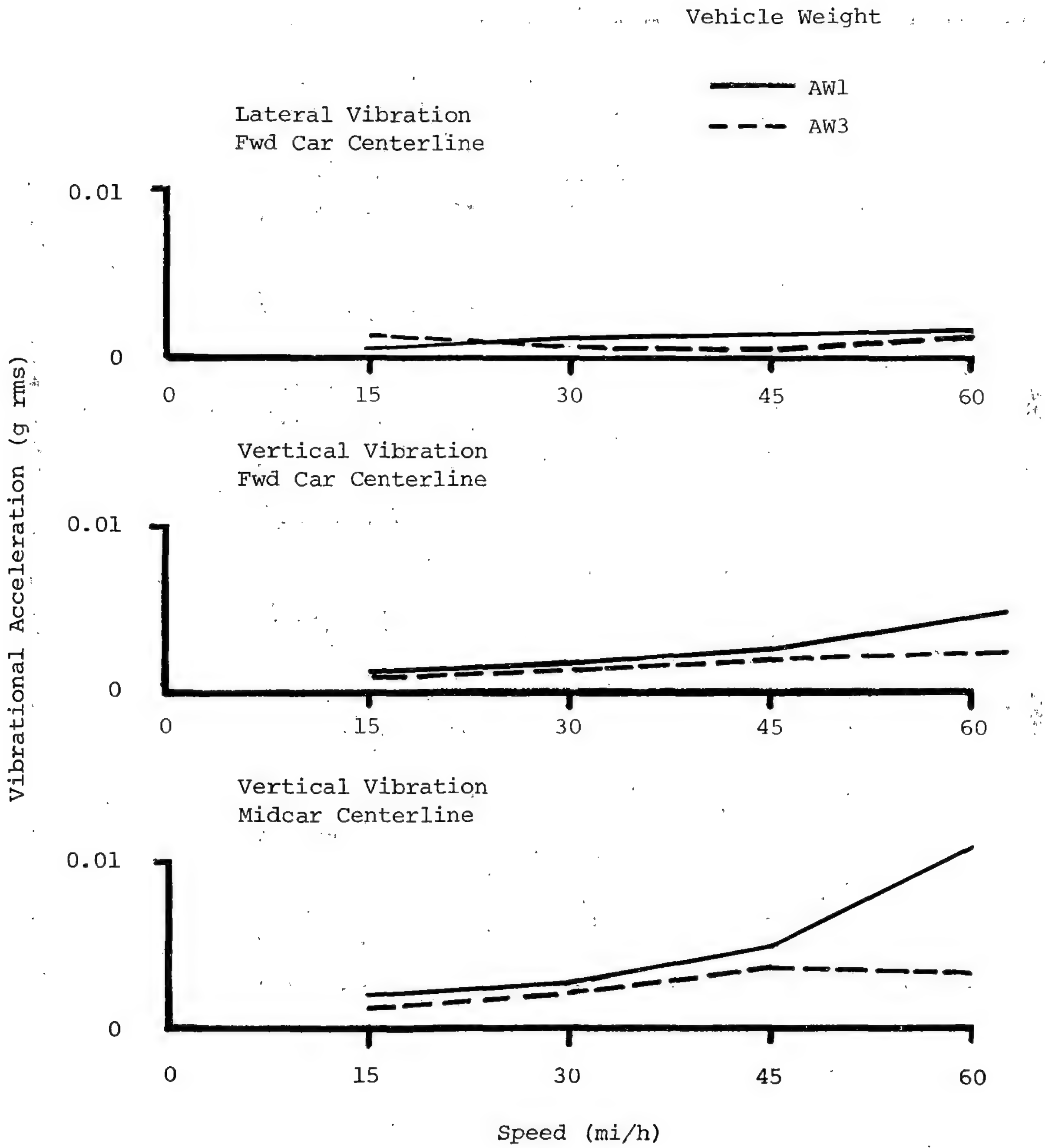

FIGURE 8-8. VIBRATION VARIATION WITH SPEED (RMS).

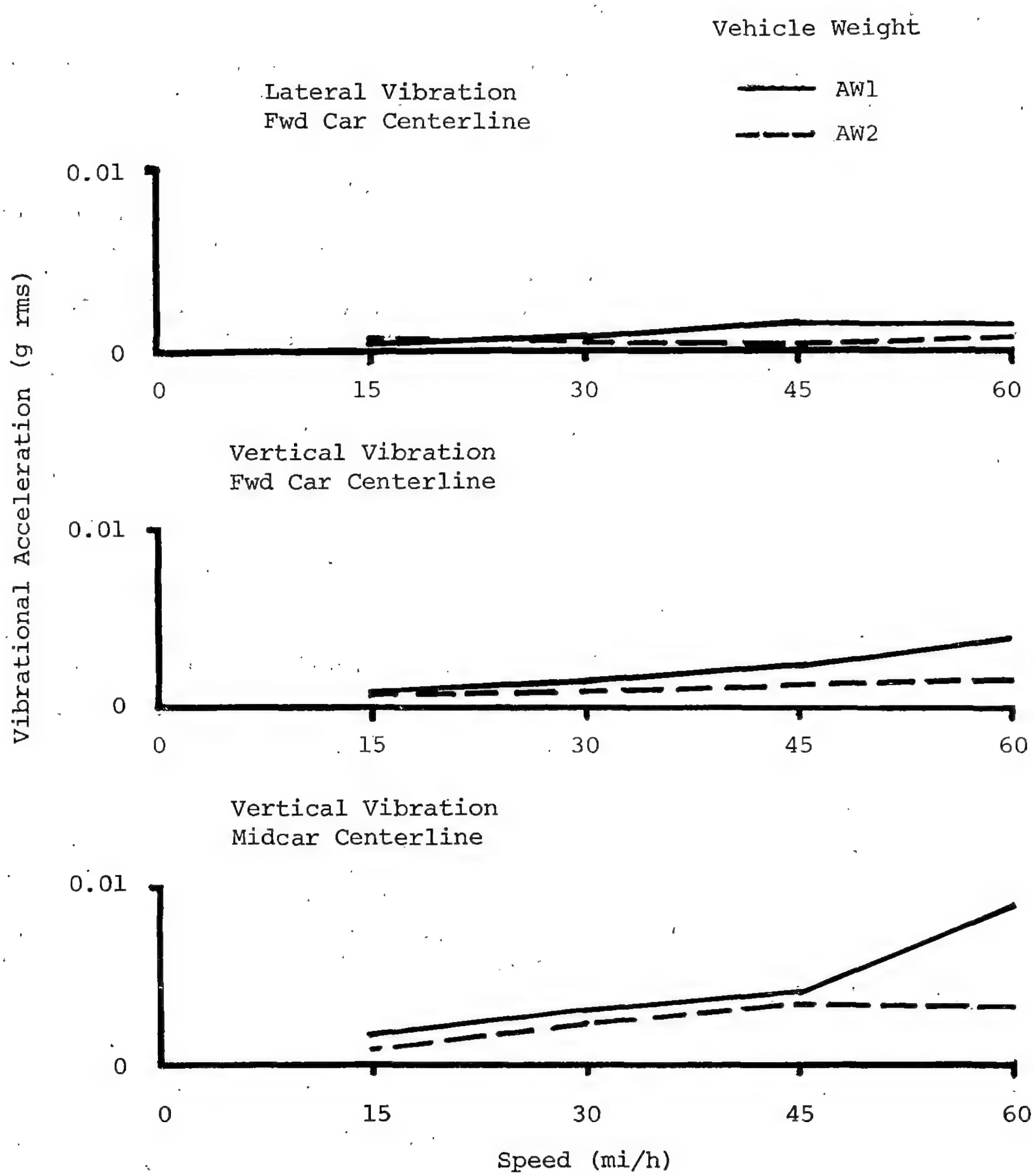

FIGURE 8-9. VIBRATION VARIATION WITH SPEED (RMS, ISO WEIGHTED).

b. Effects of speed. Typical vertical and lateral input vibration at the right front wheel bearing journal is shown as a function of speed in figure 8-10. These data are included as an input reference to the carbody motions experienced throughout the ride quality test program, and are representative of track maintained to FRA Class 6 standards.[2] Figures 8-11 to 8-13 include PSD plots of the three carbody measurements (forward vertical and lateral acceleration, midcar vertical acceleration) at each speed for car weight AW1.

Evident in all the spectral plots is the 0.6 Hz mode observed in the zero speed component-induced study, where it first appeared as a possible lower sway mode.

In all moving car measurements, a prominent feature is the carbody response in the frequency range between 1 to 3 Hz, apparently caused by a series of rigid body fundamental suspension modes. The vibration generally increased with speed. Figures 8-14, 8-15, and 8-16 illustrate the speed-dependence of the predominant frequency components observed in the carbody measurements, for forward vertical and lateral, and midcar vertical measurements, respectively.

The 1 to 3 Hz components tend to increase with speed in the vertical measurement but not in the lateral. The 9 to 12 Hz components observed in the vertical measurements become increasingly evident. The increase in level at 60 mi/h is likely to be due to the correspondence of any wheelset induced once-per-revolution input to 12 Hz, at this speed. These peaks can be traced from the journal and side frame vibrations to the carbody. A 30 Hz vibration component can also be observed predominantly in the midcar vertical measurement. It is less detectable in the forward car vertical measurement and is completely absent in the lateral direction.

c. Effects of track construction. The type of track had little effect on the frequency content of body vibration. Naturally, rougher track will stimulate greater vibration in the carbody at frequencies primarily determined by the car construction itself. Figure 8-17 presents PSD plots of carbody measurements recorded at 60 mi/h over each section of track, including the north gap and switch (track section I). The nearly identical frequency content is clearly evident in all these measurements. The predominant components are seen to be the same as those discussed earlier in this section.

Comparison of the major component levels at the various track sections shows no particular track stimulation trends in terms of vibration amplitude. Suspected track input frequencies associated with various tie spacings and rail joints are not noticeable in the spectral plots. Overall rms values at all speeds are compared in figures 8-18 through 8-21 for the three carbody measurements selected. Here again, no specific trends are evident. The high midcar vertical rms level at 60 mi/h on track section IV is the only exception; this level is manifest

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[2] Track Safety Standards, FRA Office of Safety, March 1975.

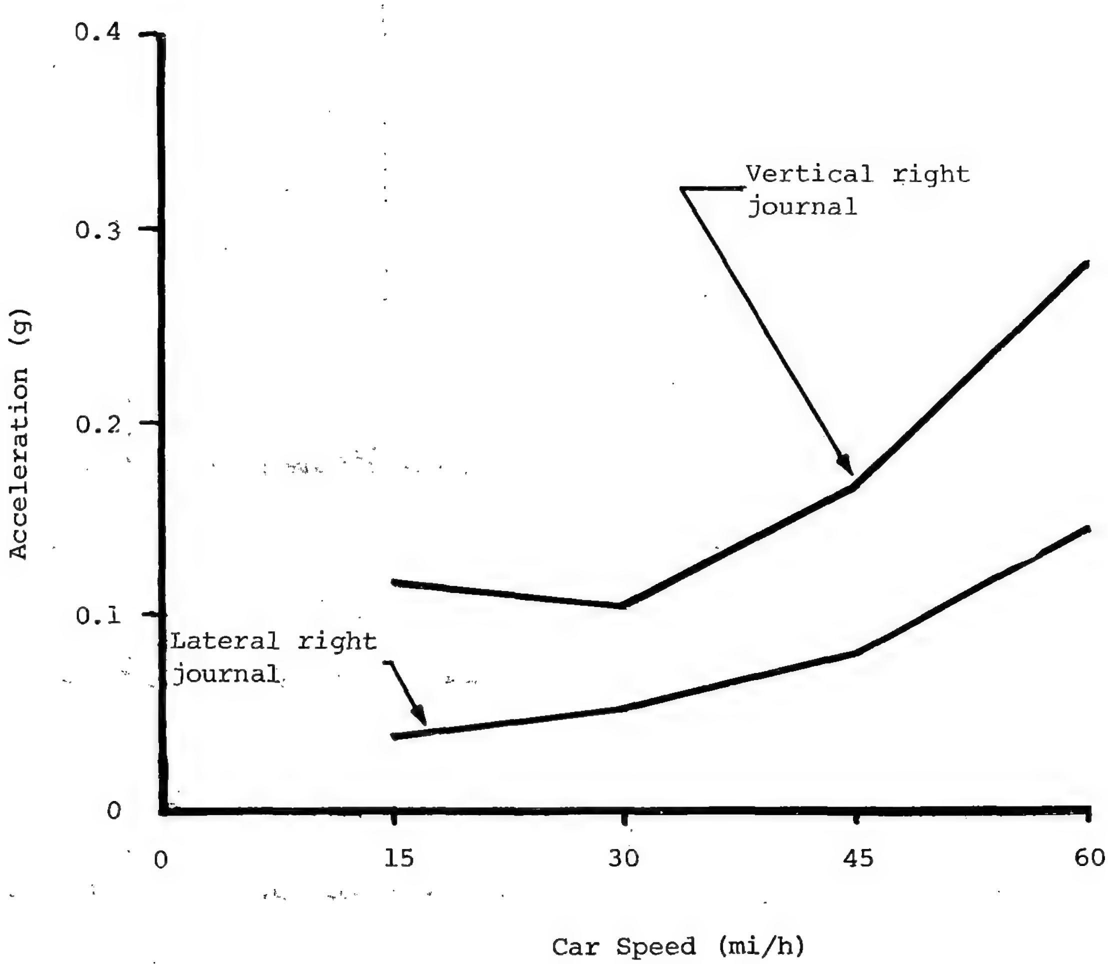


FIGURE 8-10. VARIATION OF BEARING JOURNAL VIBRATION WITH SPEED.

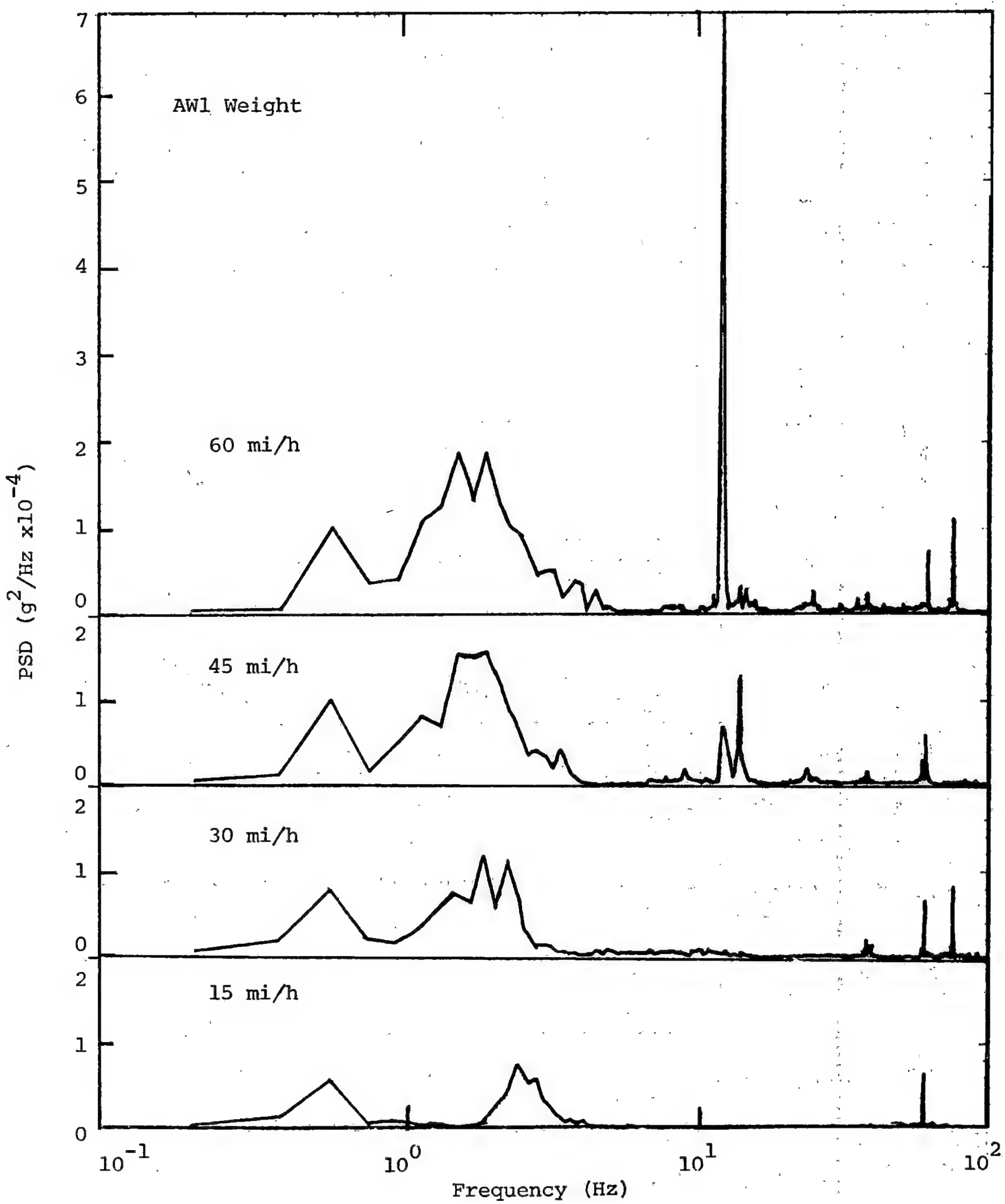


FIGURE 8-11. EFFECT OF SPEED ON FORWARD VERTICAL VIBRATION SPECTRA.

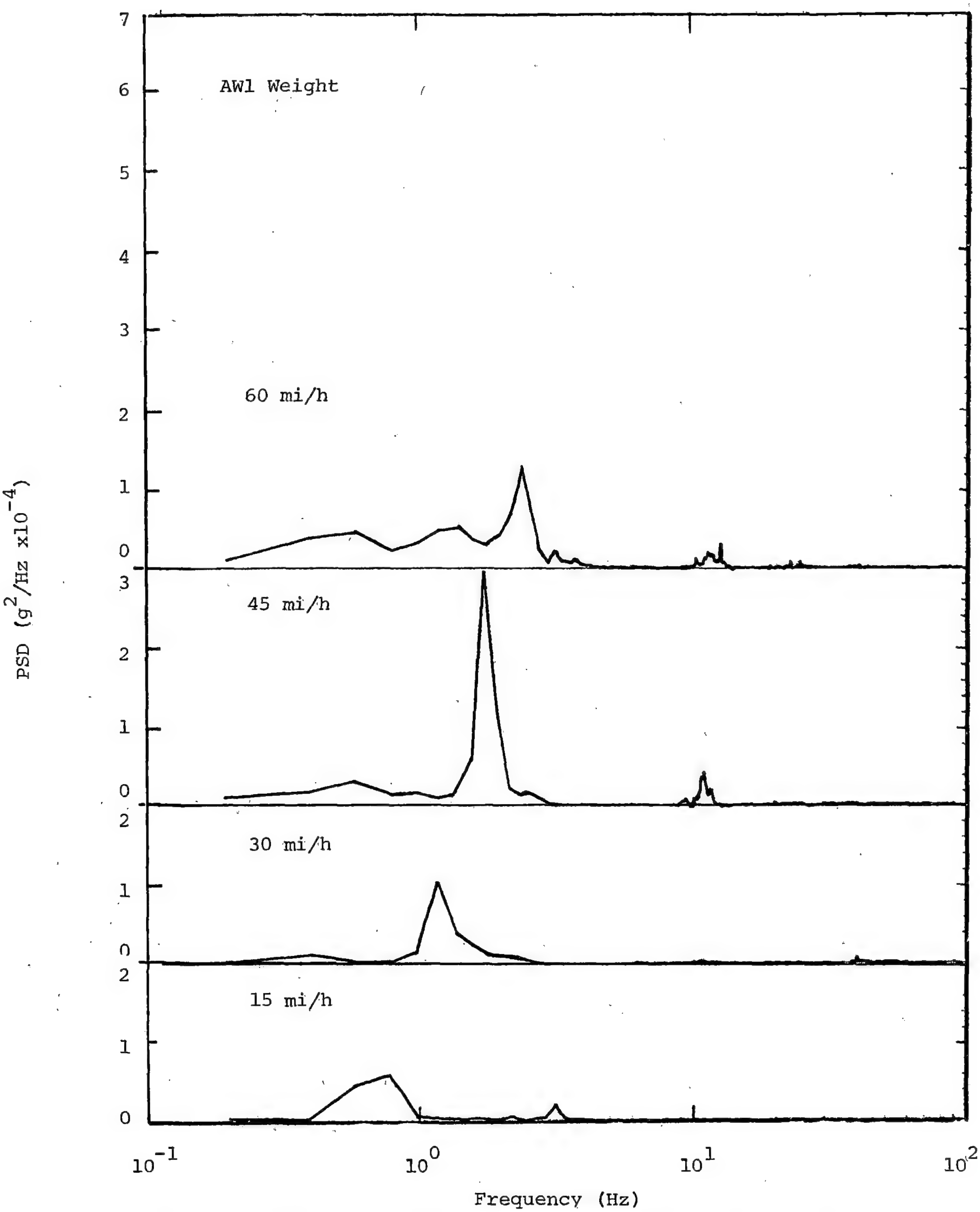


FIGURE 8-12. EFFECT OF SPEED ON FORWARD LATERAL VIBRATION SPECTRA.

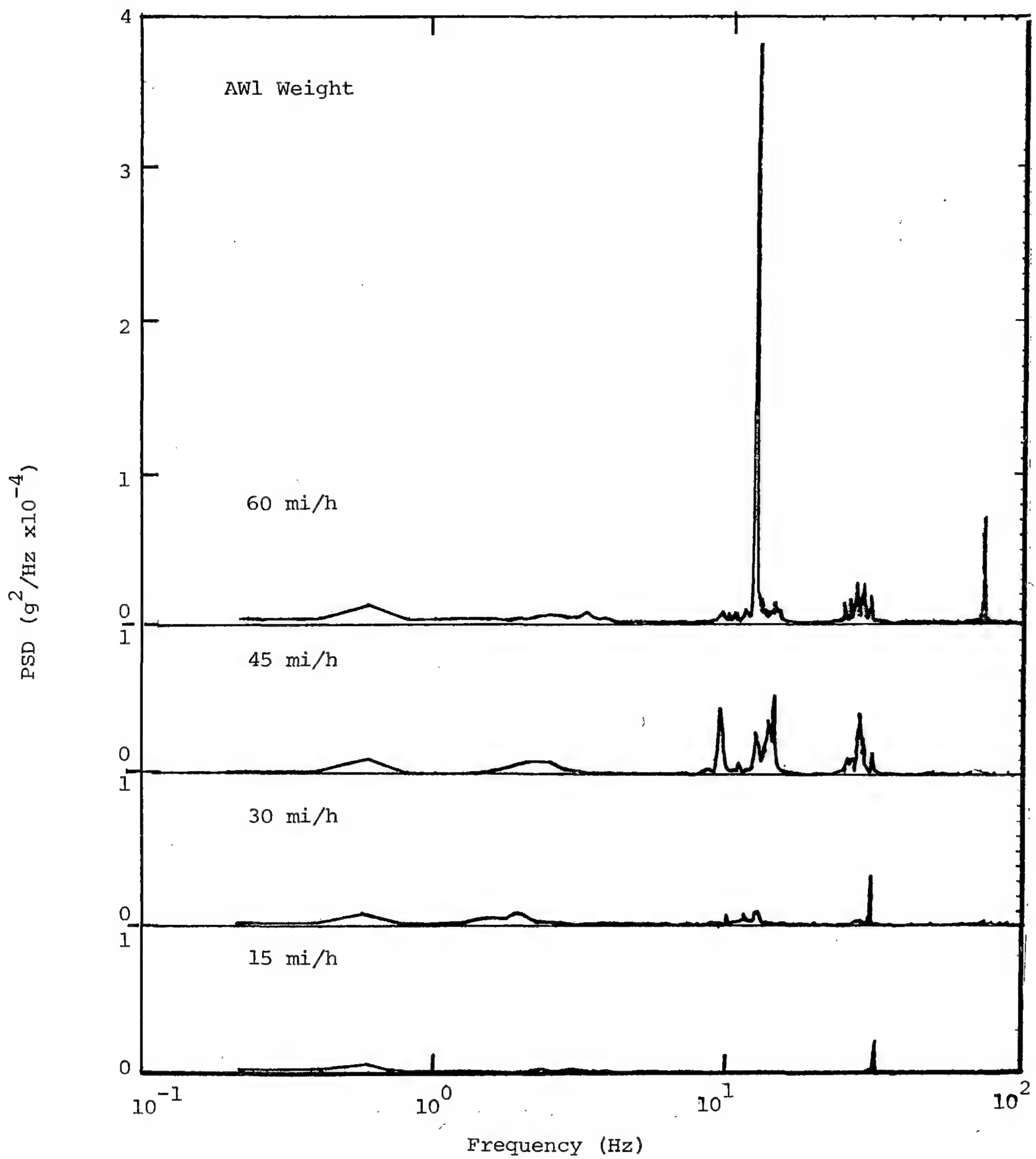


FIGURE 8-13. EFFECT OF SPEED ON MIDCAR VERTICAL VIBRATION SPECTRA.

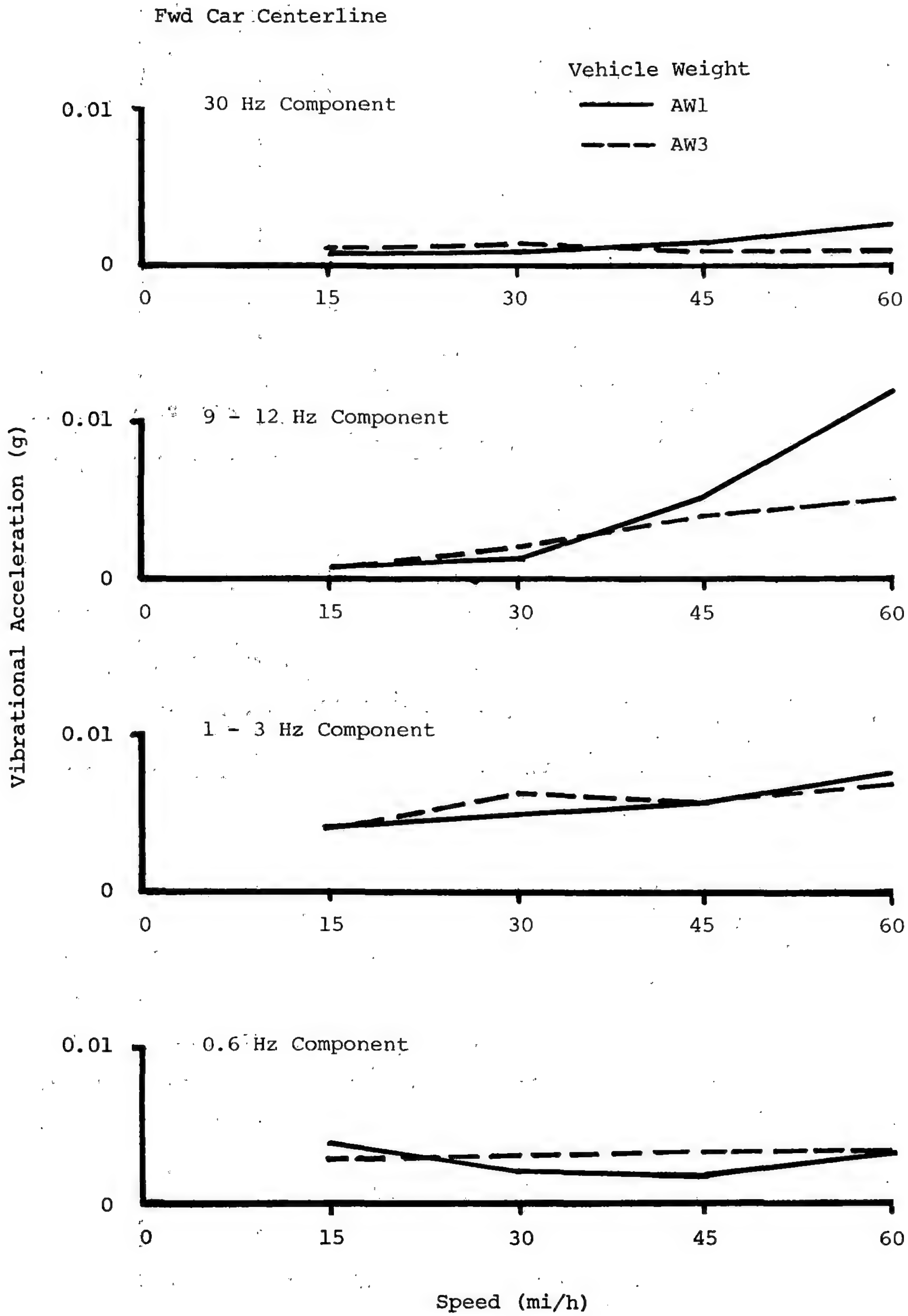


FIGURE 8-14. EFFECT OF SPEED ON FORWARD VERTICAL FREQUENCY COMPONENTS.

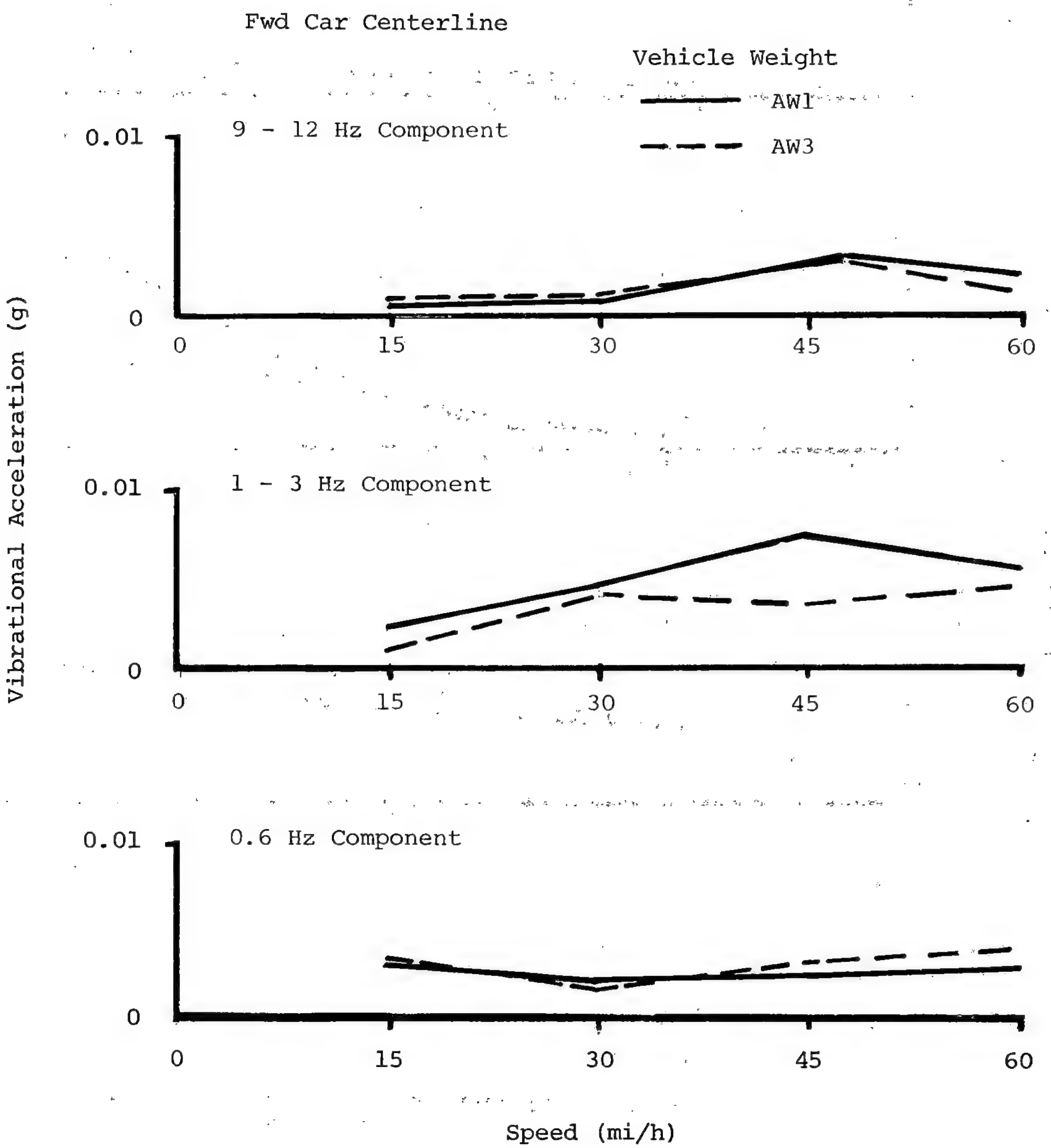


FIGURE 8-15. EFFECT OF SPEED ON FORWARD LATERAL FREQUENCY COMPONENTS.

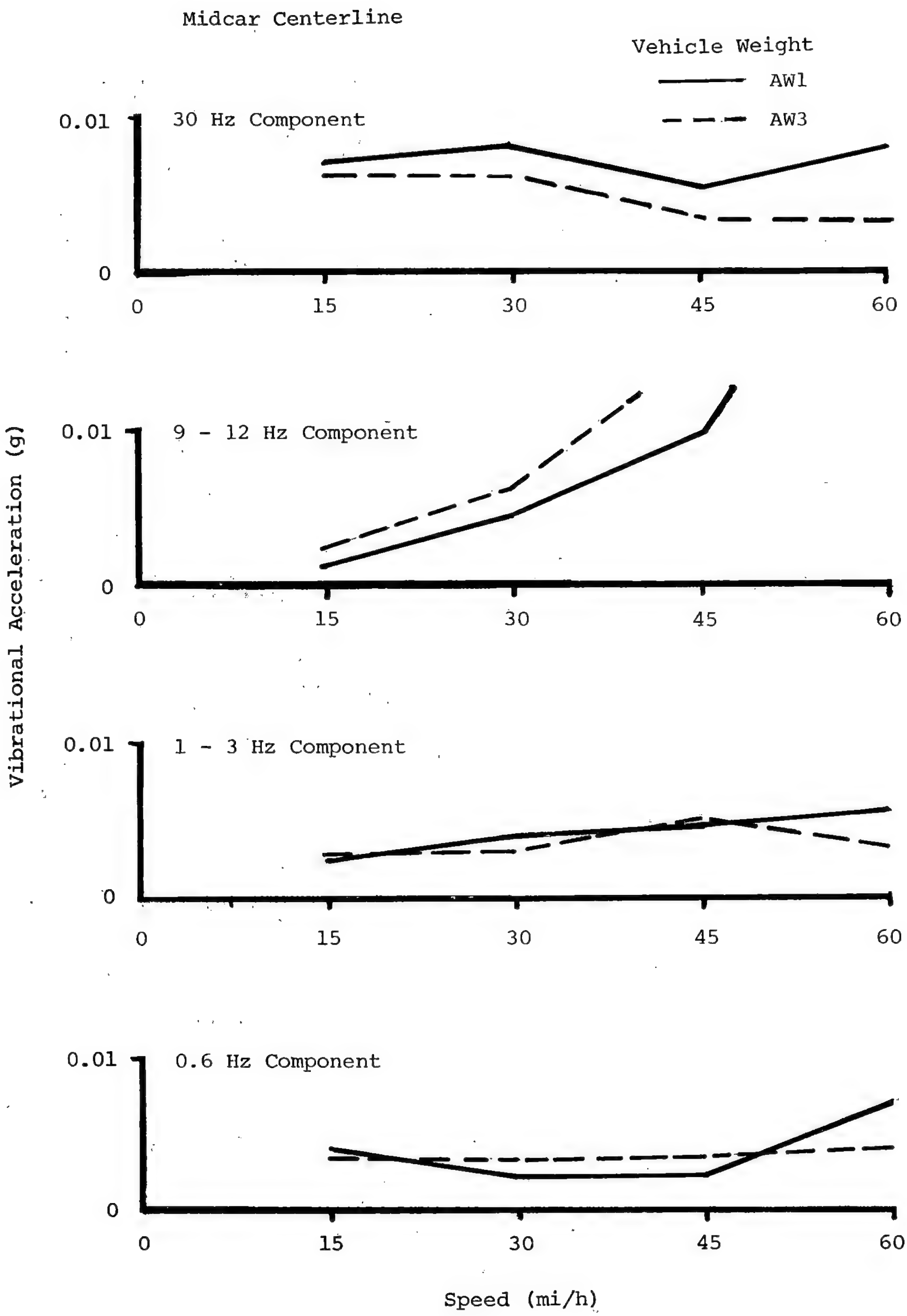


FIGURE 8-16. EFFECT OF SPEED ON MIDCAR VERTICAL FREQUENCY COMPONENTS.

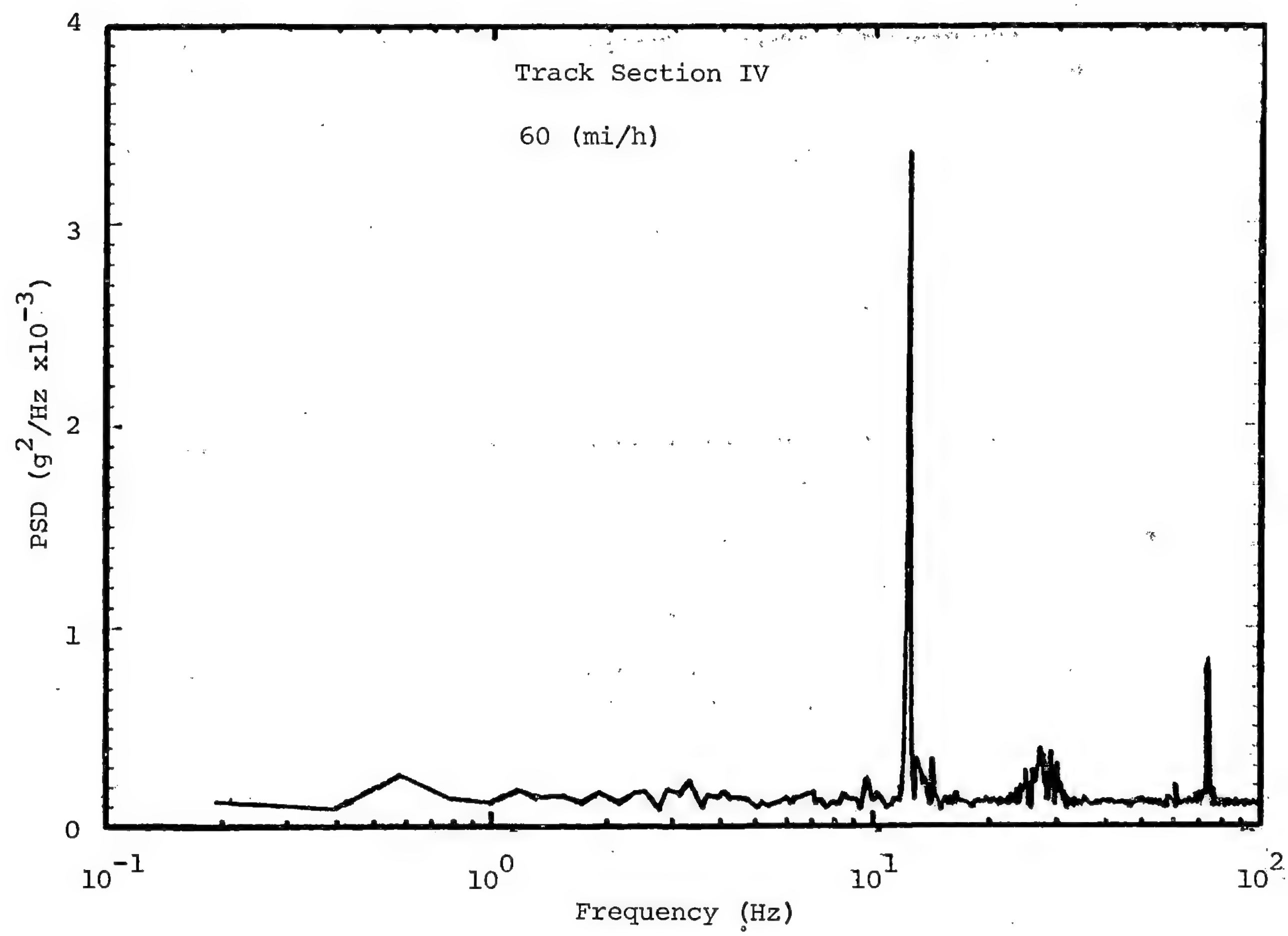


FIGURE 8-17. EFFECT OF TRACK SECTION ON CARBODY VIBRATION SPECTRA.

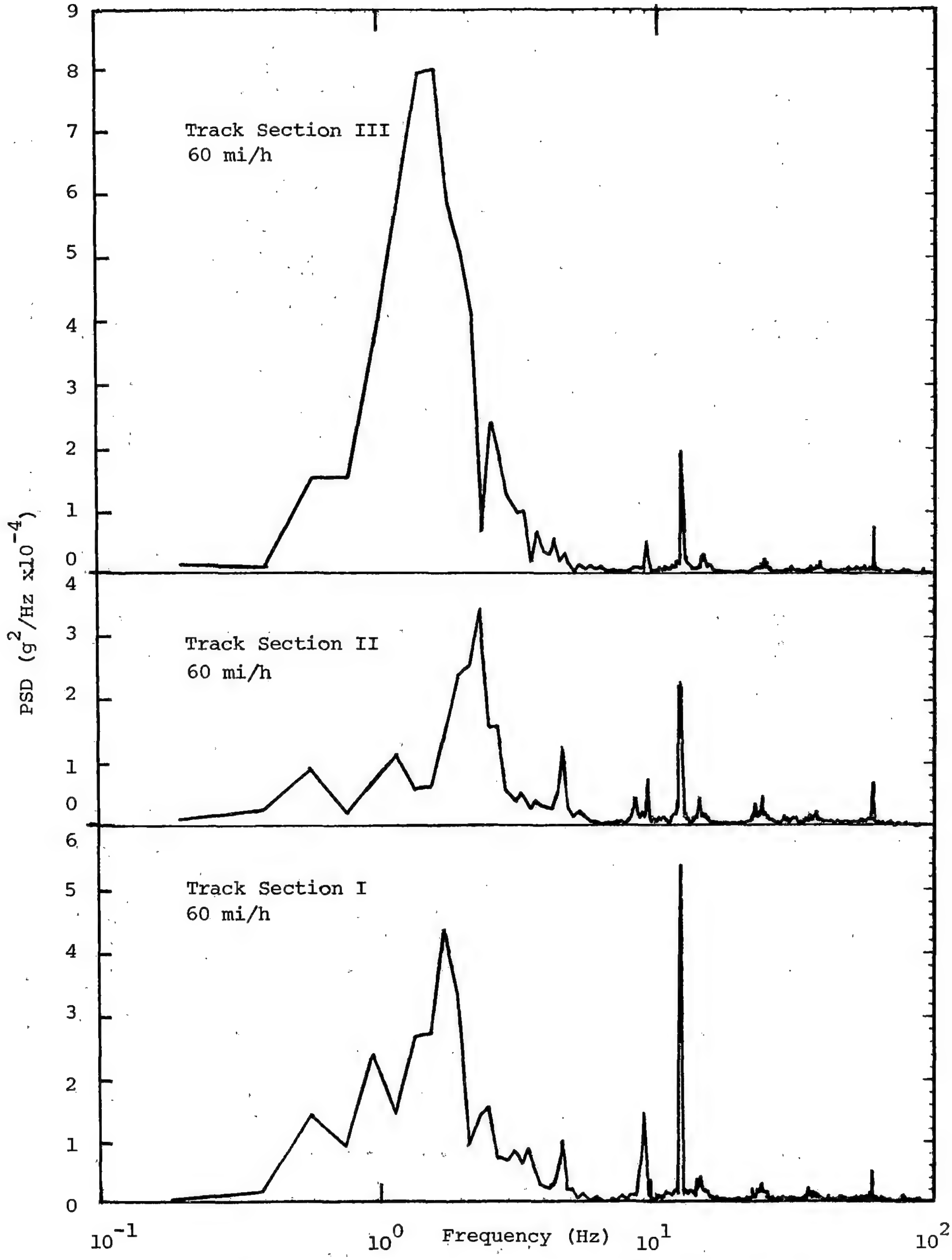
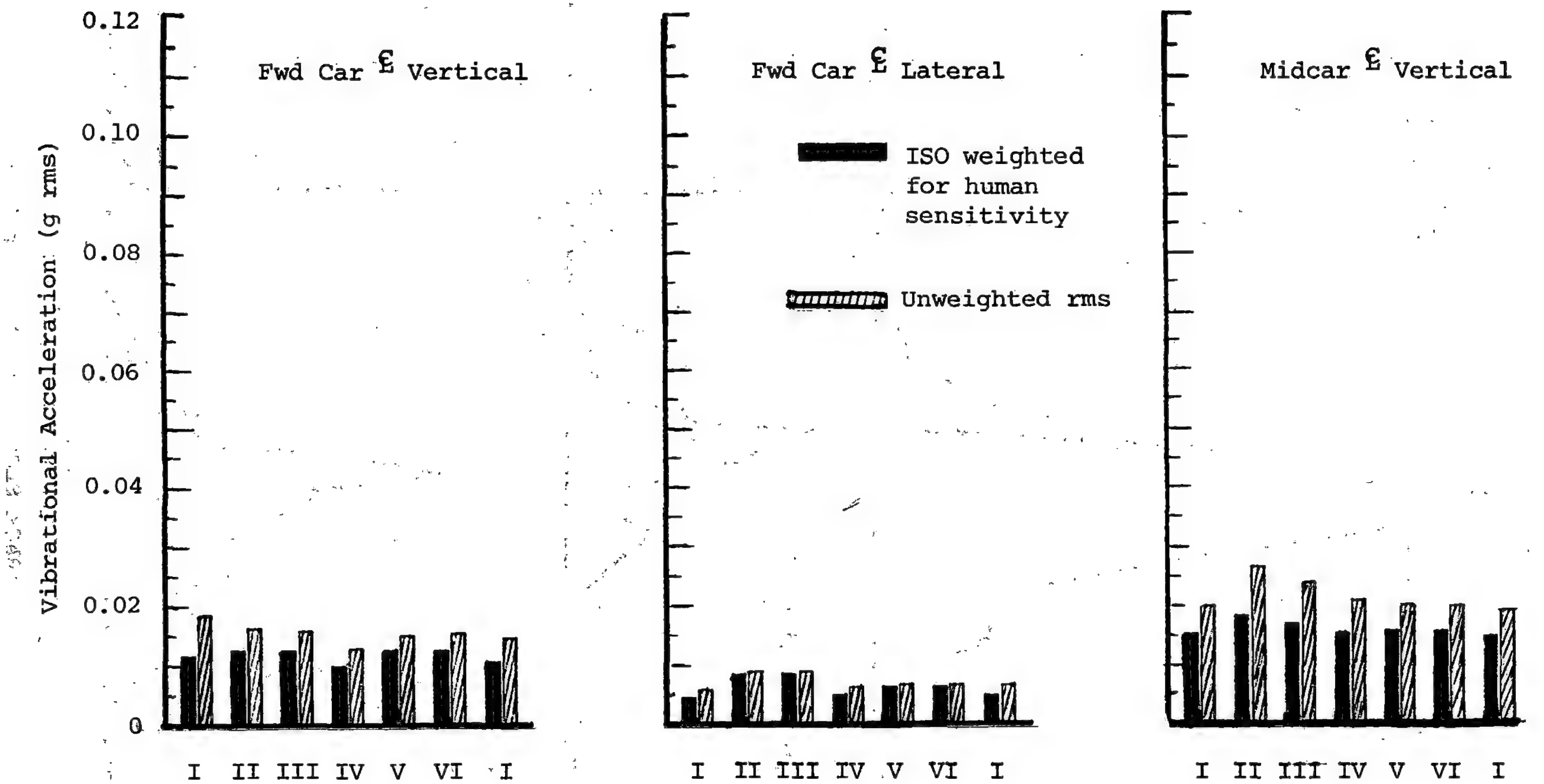
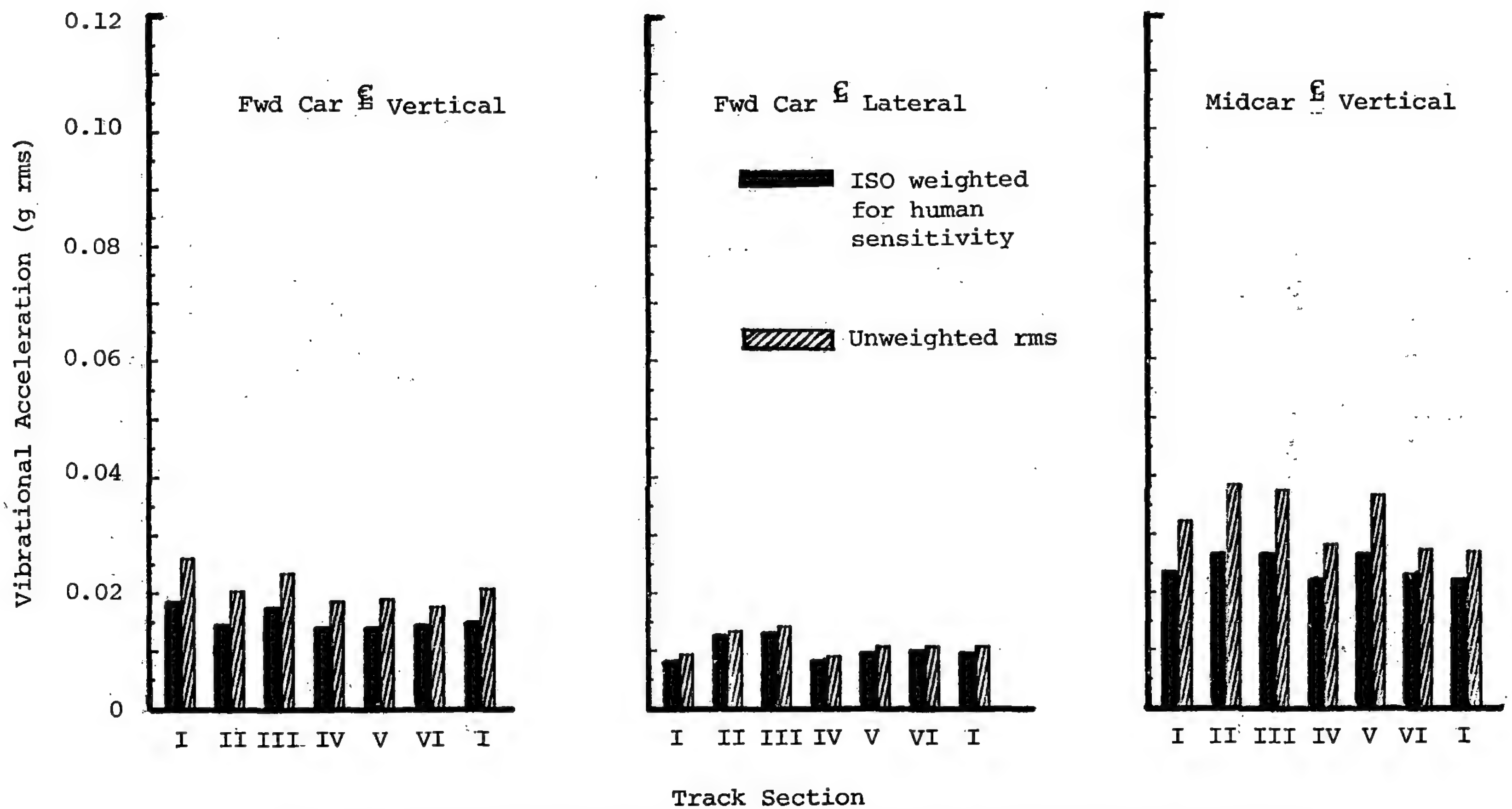


FIGURE 8-17. EFFECT OF TRACK SECTION ON CARBODY VIBRATION SPECTRA, CONTINUED.



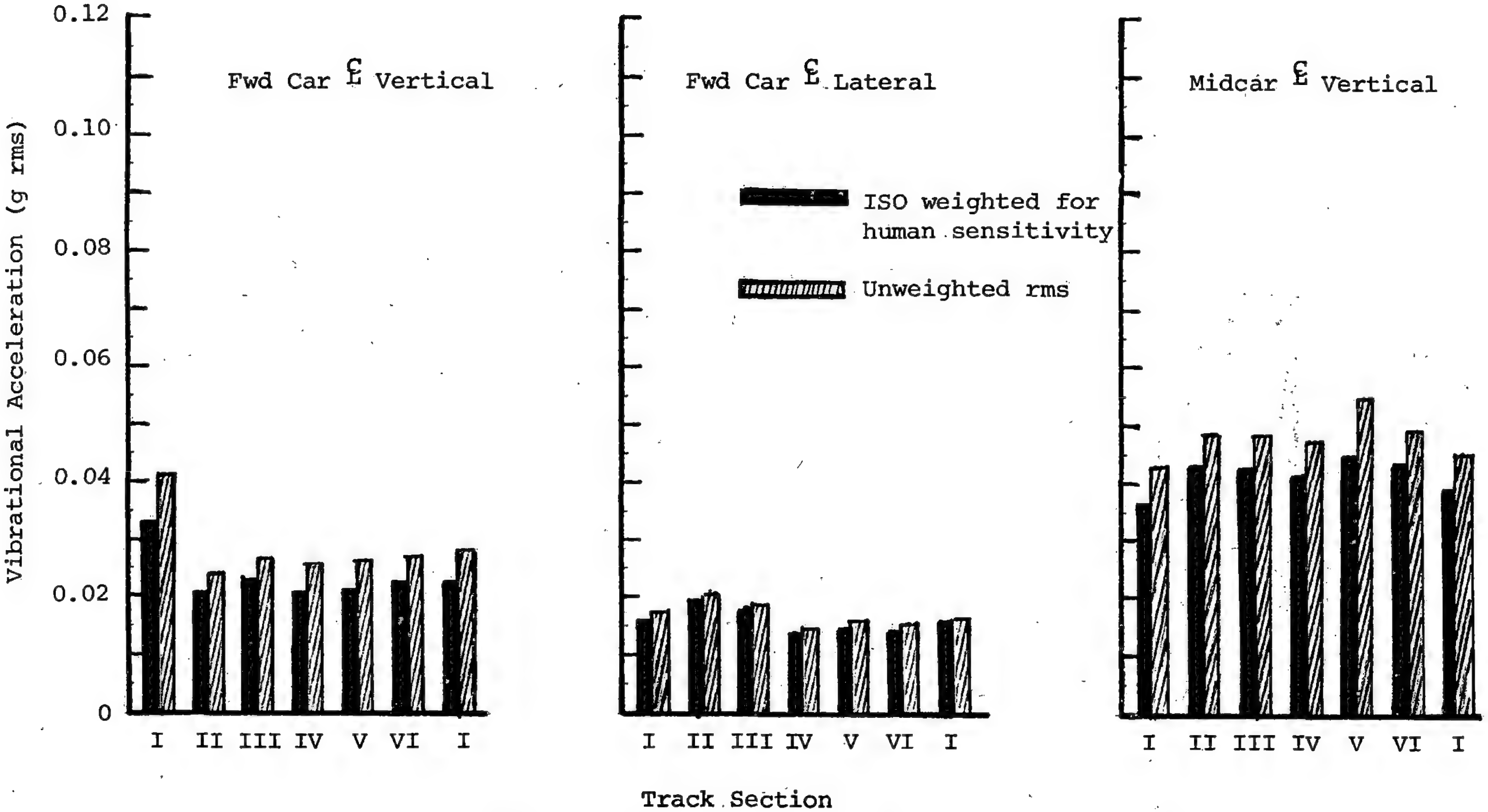
Track Section	I	II	III	IV	V	VI	I
Rail Stations	12-15	21.5-24	25.5-28	36-38.5	45-48	48-51	52-55

FIGURE 8-18. VARIATION OF VIBRATION WITH TRACK SECTION AT 15 MI/H.



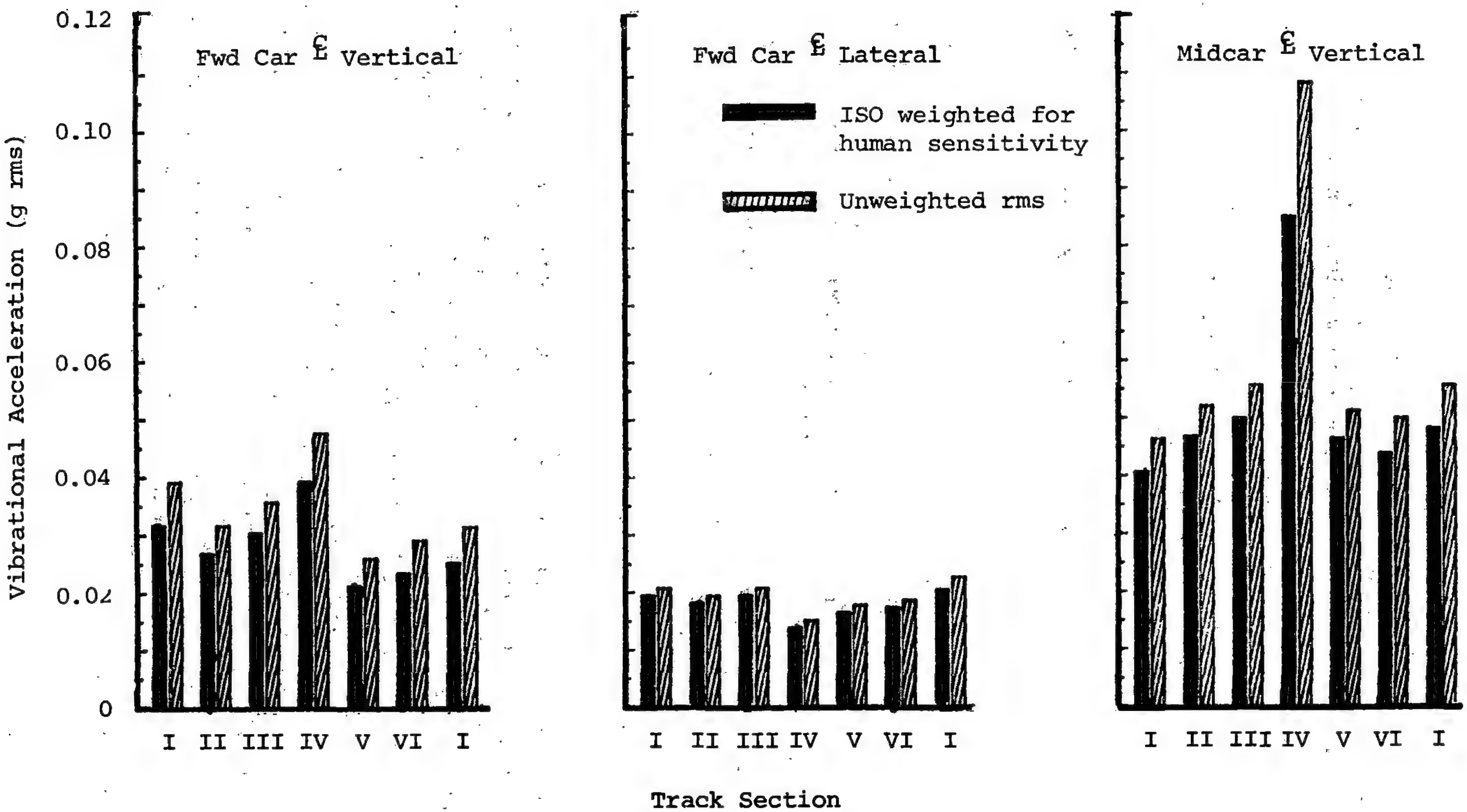
Track Section	I	II	III	IV	V	VI	I
Rail Stations	12-15	21.5-24	25.5-28	36-38.5	45-48	48-51	52-55

FIGURE 8-19. VARIATION OF VIBRATION WITH TRACK SECTION AT 30 MI/H.



Track Section Rail Stations	I 12-15	II 21.5-24	III 25.5-28	IV 36-38.5	V 45-48	VI 48-51	I 52-55

FIGURE 8-20. VARIATION OF VIBRATION WITH TRACK SECTION AT 45 MI/H.



Track Section Rail Stations	I 12-15	II 21.5-24	III 25.5-28	IV 36-38.5	V 45-48	VI 48-51	1 52-55

FIGURE 8-21. VARIATION OF VIBRATION WITH TRACK SECTION AT 60 MI/H.

spectrally in a general broadband vibration increase that is not readily explained. (Track section IV is made up of welded rail on concrete ties.) The TTT, with the exception of artificial perturbations, is maintained to FRA Class 6 standards.[2]

Overall, the vehicles exhibited good ride quality characteristics. In relation to track effects, relatively light cars operating on a well-maintained test track resulted in minimal interaction.

8.4 RIDE QUALITY DURING VEHICLE ACCELERATION

8.4.1 Test Objective

To determine the most severe vibration levels encountered during car acceleration.

8.4.2 Test Method

The test was performed in track section I at power settings, P1 through P4. The vehicle was tested at car weights AW1, AW2, and AW3. Vibration data were recorded as the vehicle accelerated from a full stop at station 30.0 to the maximum speed attained at station 34.0.

For analysis, spectral information was ensemble-averaged over the entire acceleration run. The weighted and unweighted rms values were then derived from these data ensembles.

8.4.3 Test Results

Averaged unweighted rms values for the acceleration runs at car weights AW1 and AW3 are compared in figure 8-22. Typically, vertical vibration amplitudes were highest during the P3 and P4 acceleration runs. Vibration levels over the entire frequency band (0-80 Hz) ran about 50% higher at the midcar location than over the truck. The lateral vibrations ran 40-50% lower than the corresponding vertical measurements at all positions.

Levels of carbody vertical vibration tended to be greatest at AW2 weight; this was particularly evident in the midcar measurements. Values at P1 and P4 have been omitted; at the AW3 car weight, they produced computed values an order of magnitude higher than all other measurements.

Figures 8-23, 8-24, and 8-25 illustrate trends in the major frequency components under acceleration at the four power settings for the three carbody accelerometers. The vertical vibration components peak or level off at the P3 setting with the obvious exception of the midcar 30 Hz vertical component,

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[2] Ibid.

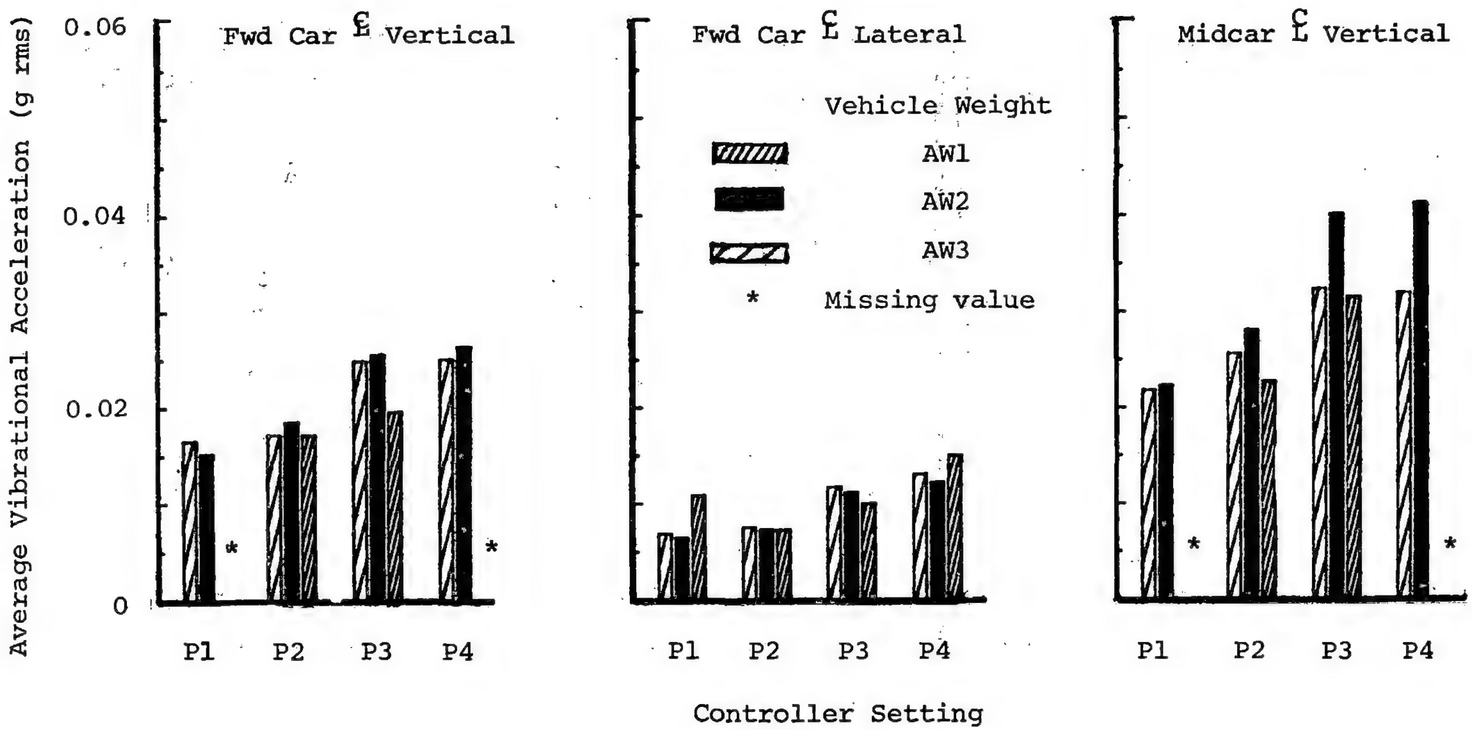


FIGURE 8-22. EFFECT OF ACCELERATION ON VIBRATION (RMS-AVERAGED).

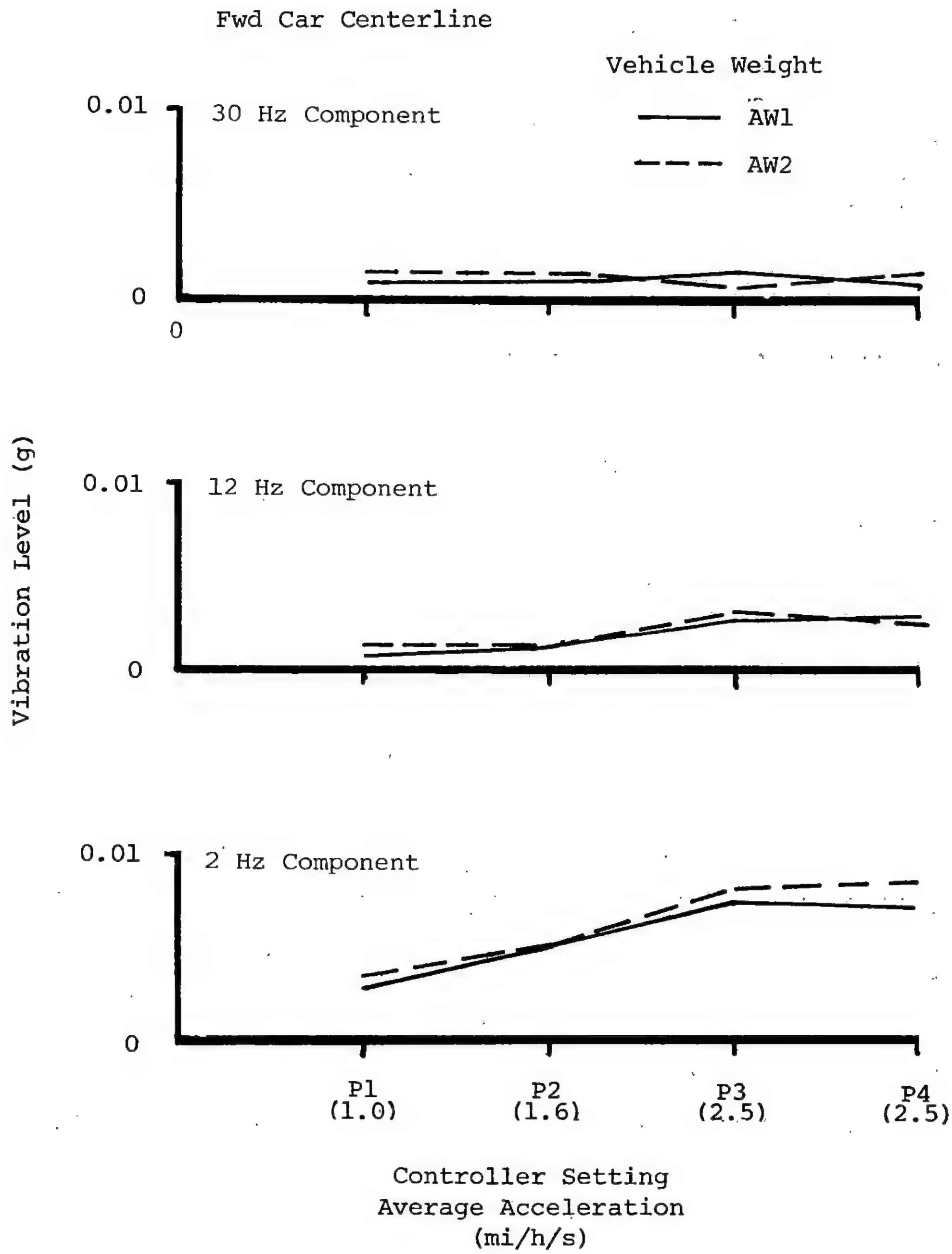


FIGURE 8-23. EFFECT OF ACCELERATION ON FORWARD VERTICAL FREQUENCY COMPONENTS.

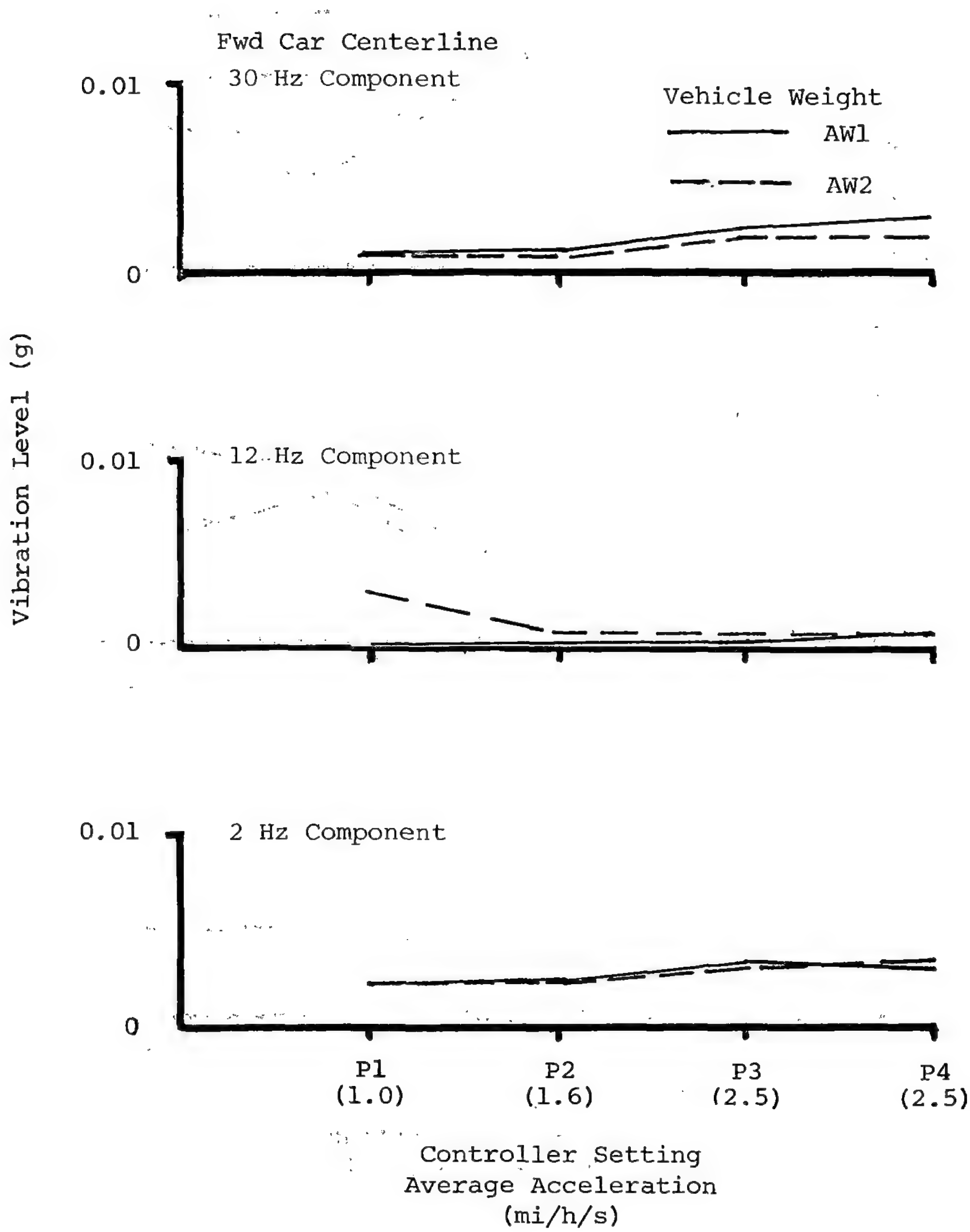


FIGURE 8-24. EFFECT OF ACCELERATION ON FORWARD LATERAL FREQUENCY COMPONENTS.

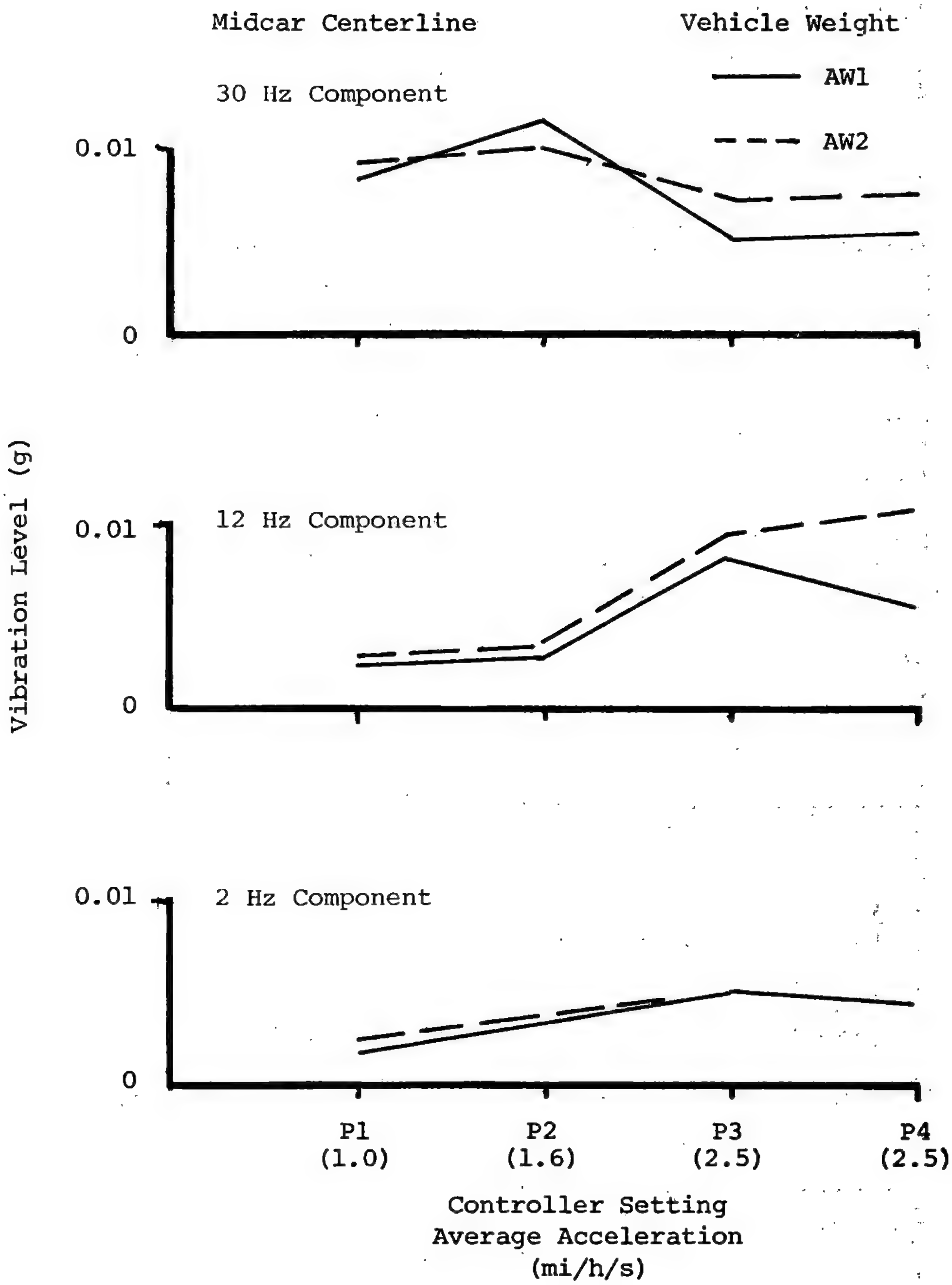


FIGURE 8-25. EFFECT OF ACCELERATION ON MIDCAR VERTICAL FREQUENCY COMPONENTS.

which indicates a peak at P2. No conclusive trends can be noted in lateral components as a function of the car weight.

8.5 RIDE QUALITY DURING VEHICLE BRAKING

8.5.1 Test Objective

To determine the most severe vibration levels encountered during vehicle deceleration due to full service braking.

8.5.2 Test Method

The vehicles were operated at initial speeds of 60, 50, 40, 30, 20, and 10 mi/h for braking vibration testing. These tests, like the acceleration tests, were performed on level tangent track at vehicle test weights AW1, AW2, and AW3. At station 30.0, full service braking was applied, and vibration measurements were recorded from station 30.0 until the vehicle came to a complete stop.

Spectral information was ensemble-averaged over the entire deceleration run in the same manner as for the acceleration data. Weighted and unweighted rms values were then derived from the data ensembles.

8.5.3 Test Results

Figure 8-26 compares the averaged rms vibration levels for all the deceleration runs. As seen in previous data, the midcar vertical vibrations show the highest levels. Lateral vibration was typically 40-50% lower than the corresponding vertical vibration. All vibrations tended to reach the maximum level during braking from initial speeds of 40 mi/h or higher. The vibration induced in the carbody was unaffected by the simulated passenger load.

Figures 8-27, 8-28, and 8-29 present a summary of the major vibrational components observed in the spectral displays. The figures illustrate the component trends under maximum braking from initial speeds of 10, 20, 30, 40, 50, and 60 mi/h. The highest amplitudes are consistently observed in the midcar vertical measurement (figure 8-29) at AW1 vehicle weight, where the 1 to 3 Hz rigid body component reaches 0.013 g from an initial speed of 20 mi/h. The 10 and 30 Hz components of the midcar vertical measurement show slight increases with initial speed. In vertical and lateral measurements taken over the forward truck, the 30 Hz component predominates with highest peaks occurring between 40-50 mi/h initial speeds. The 2, 3, and 10 Hz components in these forward car measurements remain relatively constant over the initial braking speed range tested. Figures 8-30 and 8-31 include PSD's of the vertical vibration recorded during maximum braking from each incremental speed.

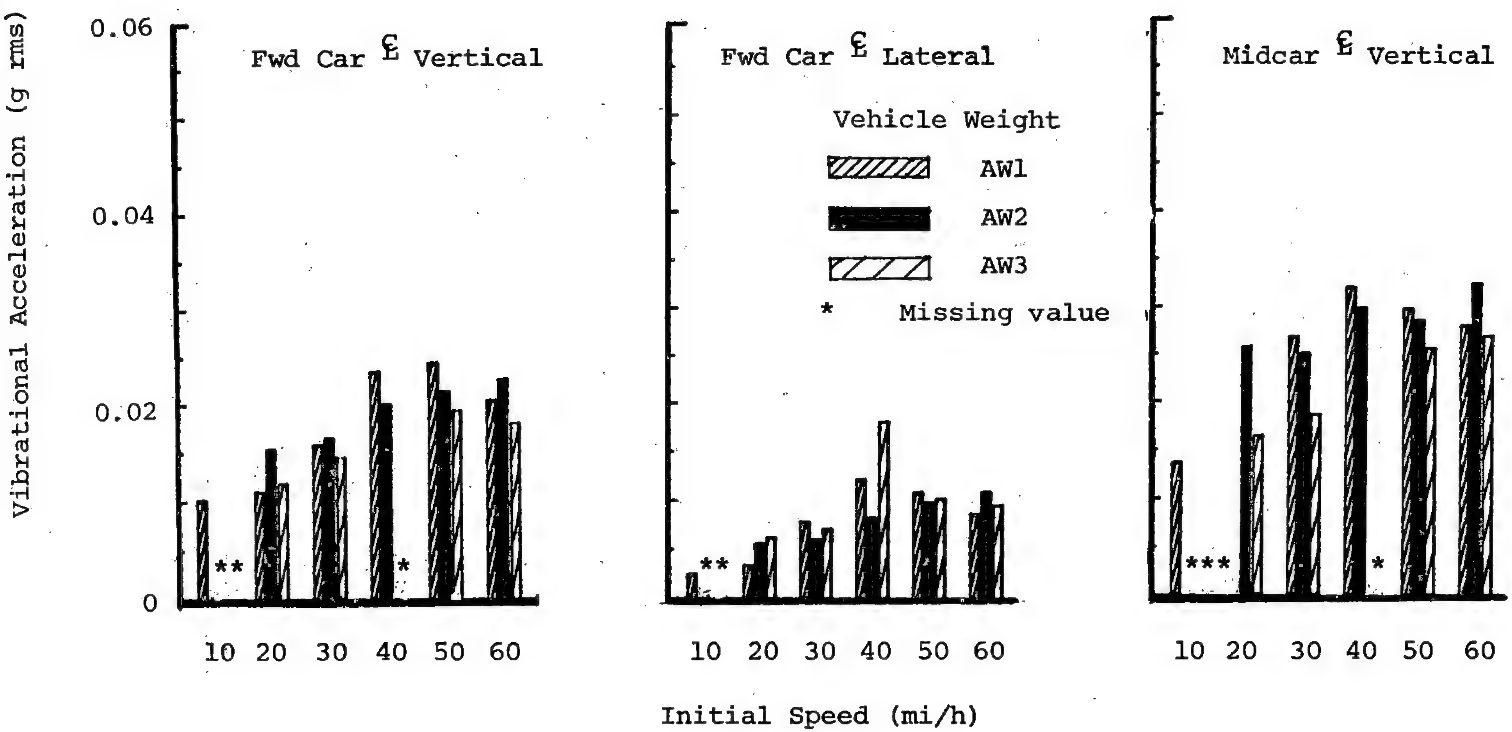


FIGURE 8-26. AVERAGE VIBRATION LEVELS, FULL SERVICE BRAKING.

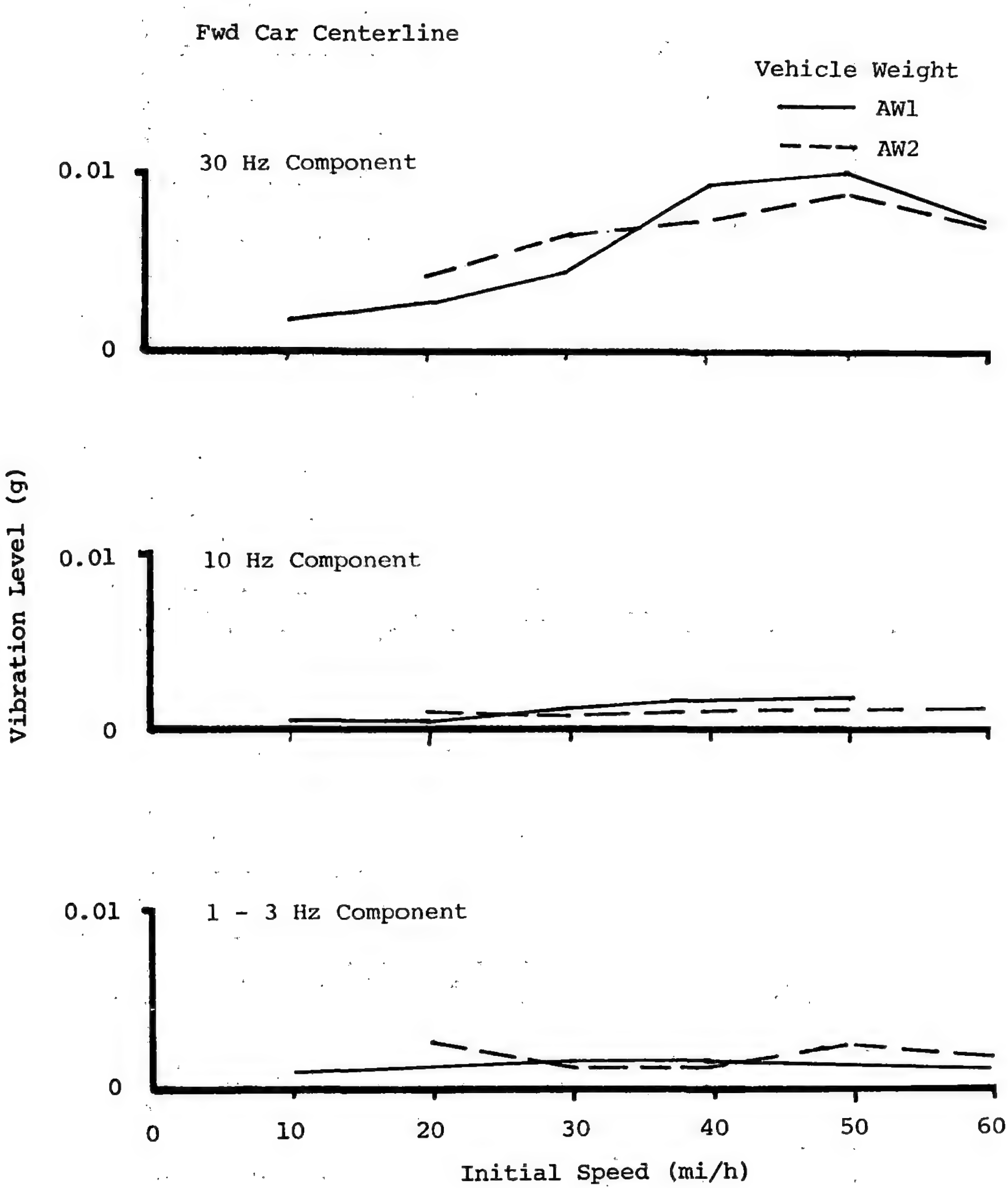


FIGURE 8-27. EFFECT OF FULL SERVICE BRAKING ON FORWARD VERTICAL VIBRATION FREQUENCY COMPONENTS.

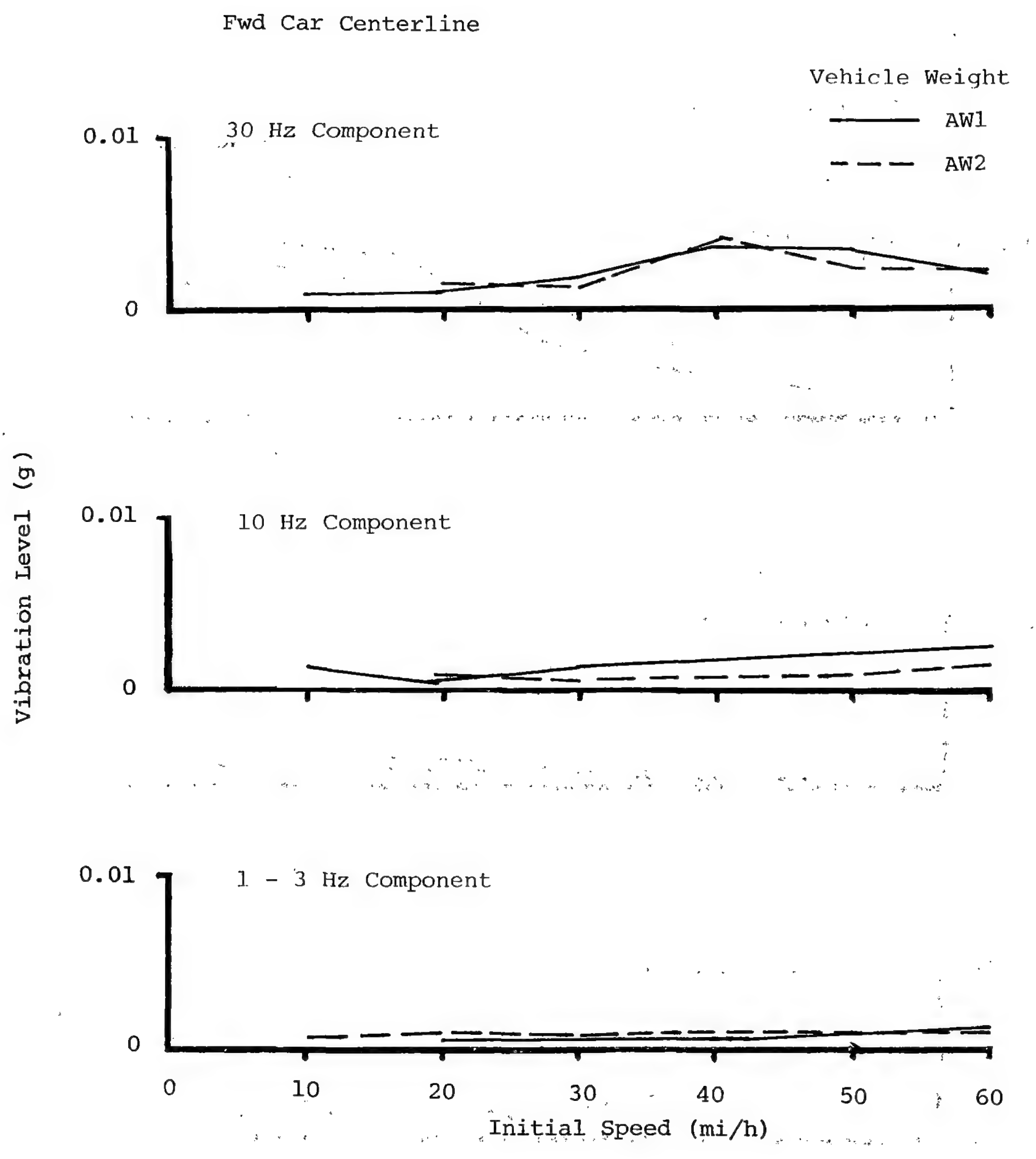


FIGURE 8-28. EFFECT OF FULL SERVICE BRAKING ON FORWARD LATERAL VIBRATION FREQUENCY COMPONENTS.

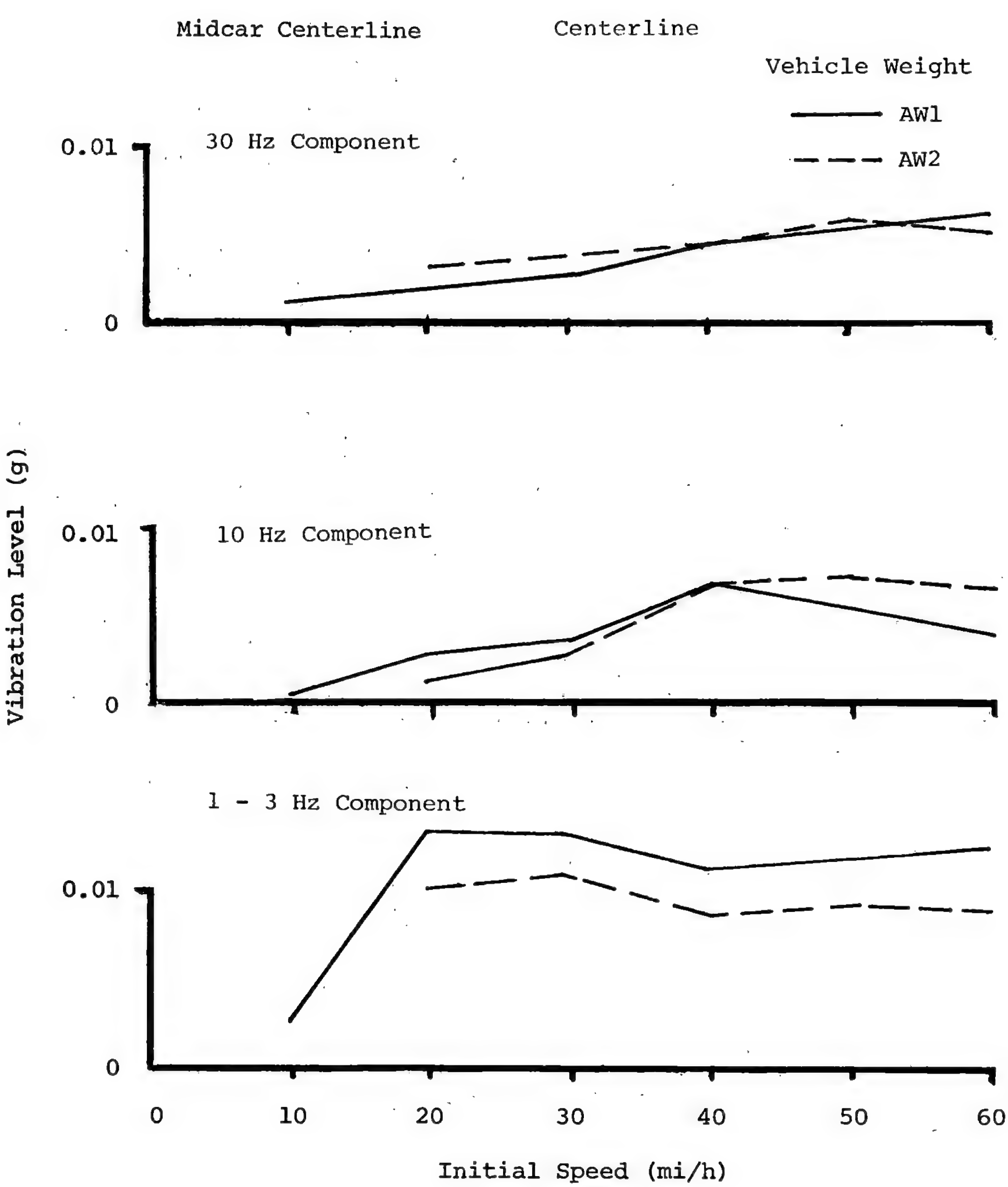


FIGURE 8-29. EFFECT OF FULL SERVICE BRAKING ON MIDCAR VERTICAL FREQUENCY COMPONENTS.

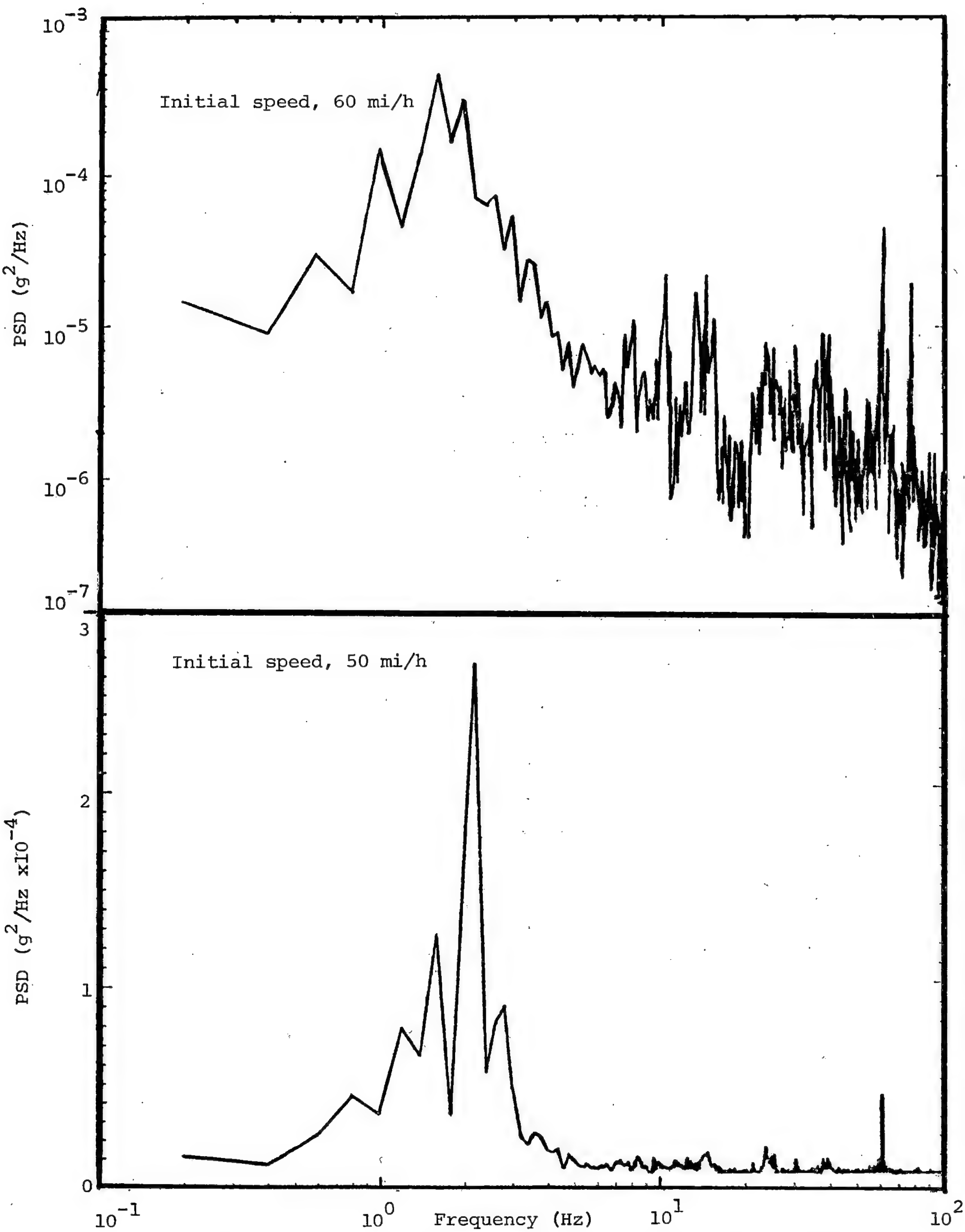


FIGURE 8-30. EFFECT OF DECELERATION FROM 60, 50 MI/H ON FORWARD VERTICAL VIBRATION SPECTRA.

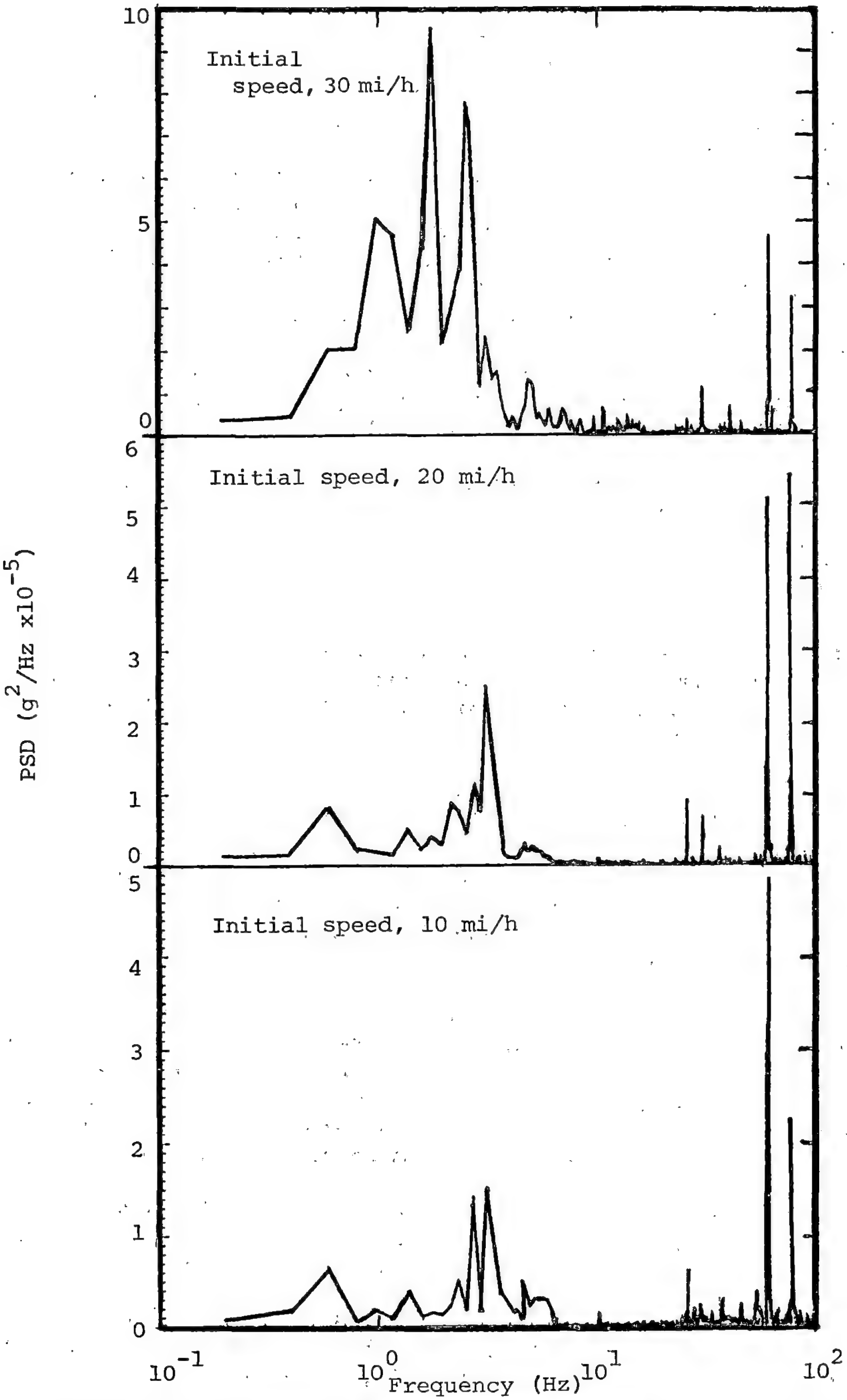


FIGURE 8-31. EFFECT OF DECELERATION FROM 30, 20, 10 MI/H ON FORWARD VERTICAL VIBRATION SPECTRA.

a. Vibration transmission through the vehicle. Accelerometers were mounted on the bearing journals and on the truck to measure vibration transmitted through the vehicle, truck, and traction motor. The PSD's of figures 8-32 through 8-36 illustrate vertical vibration input recorded at the wheel bearing journals, and response at the truck side frame, traction motors, and the forward and mid carbody locations. The lateral vibration input is similarly illustrated in figures 8-37 through 8-40. The 13, 37, 60, and 76 Hz components are prominent features in the journal PSD of figure 8-37. A low frequency spike (below 1 Hz) is also present and a broadband level is indicated near 23 Hz. As the vibration is transmitted through the primary suspensions to the truck side frame (figure 8-38), the 13 Hz component is seen to increase significantly. The 37 and 76 Hz components are attenuated by a factor of 10 or more, while the 60 Hz content broadens and shifts slightly lower in frequency. The traction motor/gear box environment (figure 8-39) is characterized by the same major frequency components. The 37 Hz content is greatly attenuated, while the range of frequency near 25 Hz appears more prominent. Here again, the low frequency resonance (below 1 Hz) is observed.

Above 3 Hz, lateral vibration in the truck frame is broadly attenuated as it is transmitted through the secondary suspension system to the carbody (forward carbody lateral vibration spectra are shown in figure 8-40). The major excitation components, however, are still evident in the spectrum. The low frequency content (below 3 Hz) is almost the same, a characteristic of a fundamental suspension mode. Tracing the vibration spectral content from the wheel input to the carbody is instructive, but the rigorous evaluation of these modal frequencies within the vehicle component systems can only be accomplished with the aid of extensive modal analysis.

b. Ride quality summary. Generally, the MBTA Blue Line cars exhibited very low vibration. At constant speed, the highest rms levels (0.055 g) were recorded at 60 mi/h and AW1 weight. Under acceleration, rms amplitudes up to 0.042 g were recorded in the midcar vertical measurement at AW2 weight, P4 controller setting. For deceleration runs, the highest rms amplitude recorded, 0.032 g, occurred under maximum braking conditions at 60 mi/h, AW2 car weight.

Comparing averaged peak levels of acceleration, the highest frequency component at constant speed occurred at 60 mi/h in the midcar vertical measurement (0.025 g at 10 Hz). During acceleration, the highest frequency component occurred during a P2 controller setting (0.011 g at 30 Hz). Similarly, braking gave a highest amplitude component of 0.014 g rms at 30 Hz for a 20 mi/h stop at AW1 weight.

The highest amplitude components in lateral and forward car vertical measurements were typically the 1 to 3 Hz rigid body mode components. They were observed consistently in all ride quality runs.

The Blue Line vehicles met the only specification requirement for ride quality, that interior vibration levels due to operation of the undercar equipment should not exceed 0.04 g instantaneous.

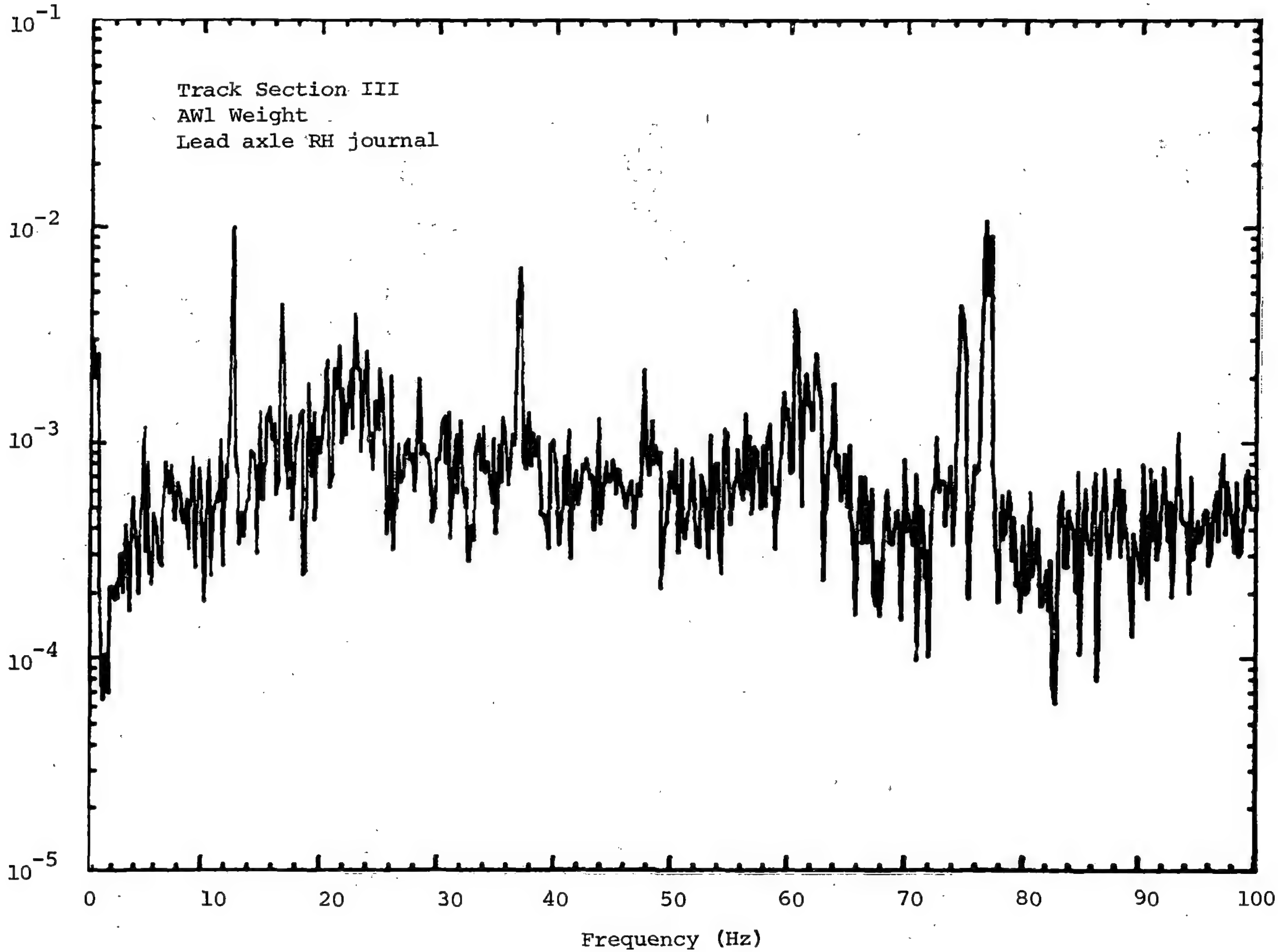


FIGURE 8-32. JOURNAL BEARING VERTICAL VIBRATION SPECTRA AT 60 MI/H.

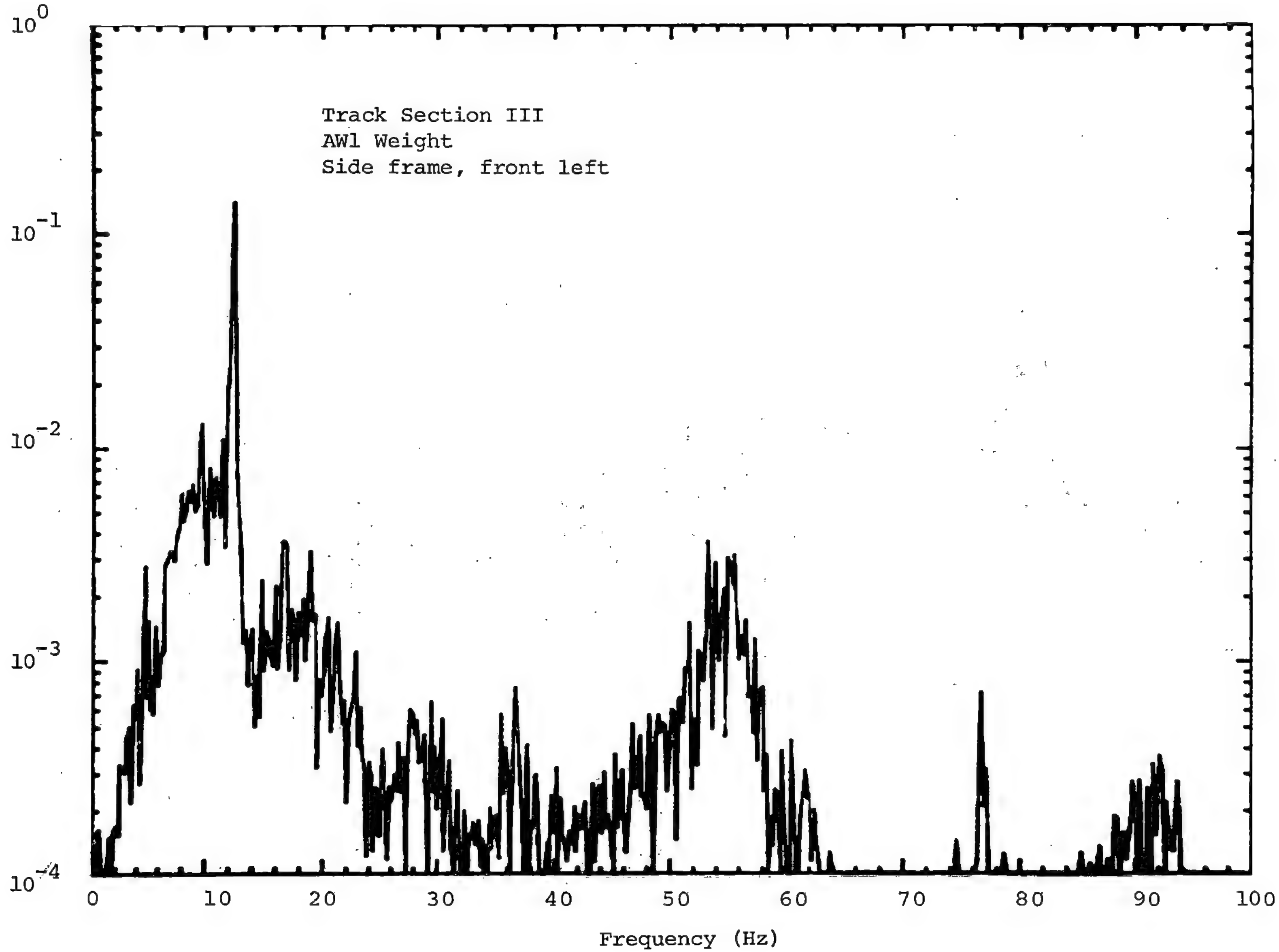


FIGURE 8-33. TRUCK SIDE FRAME VERTICAL VIBRATION SPECTRA AT 60 MI/H.

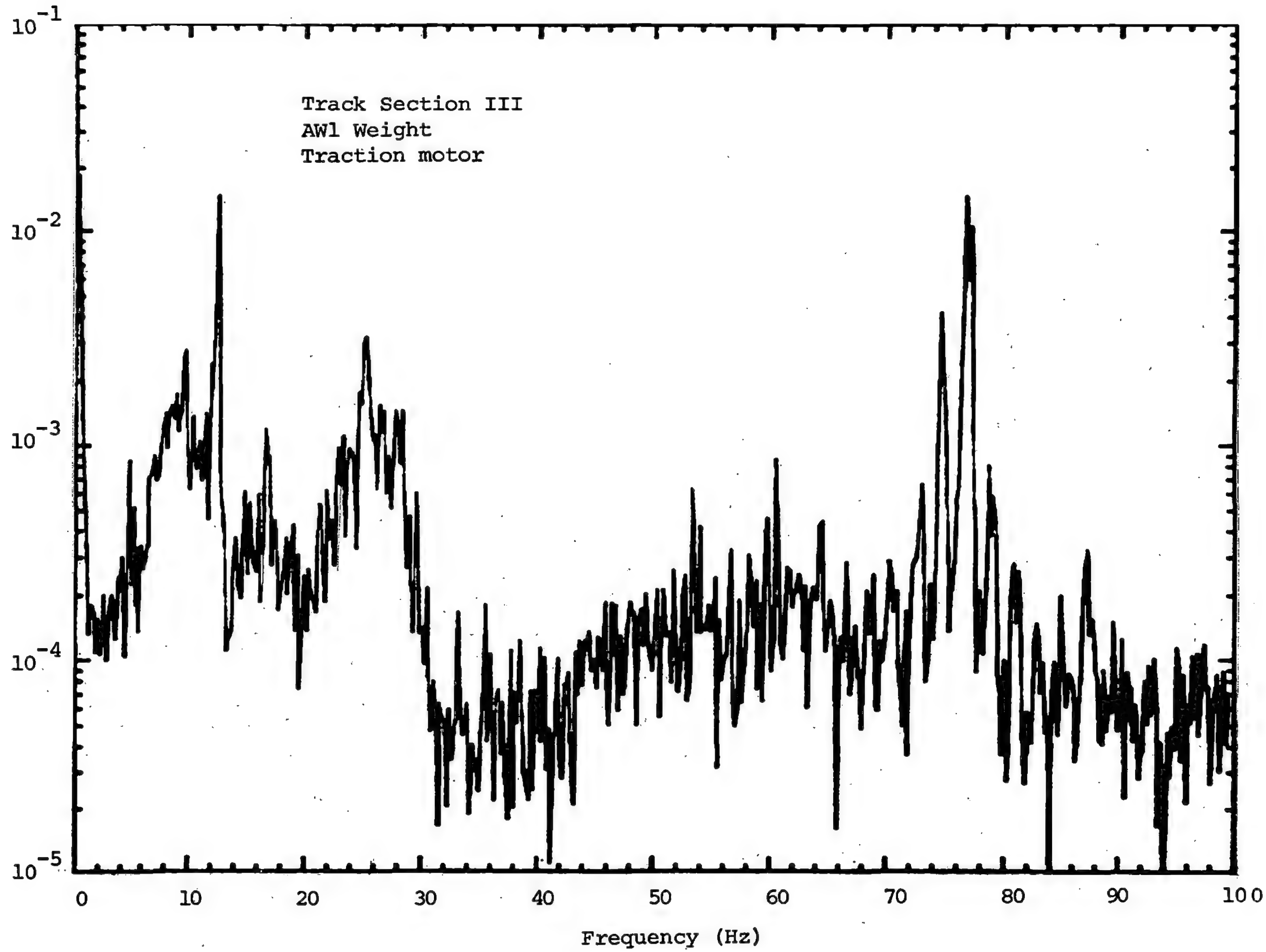


FIGURE 8-34. TRACTION MOTOR VERTICAL VIBRATION SPECTRA AT 60 MI/H.

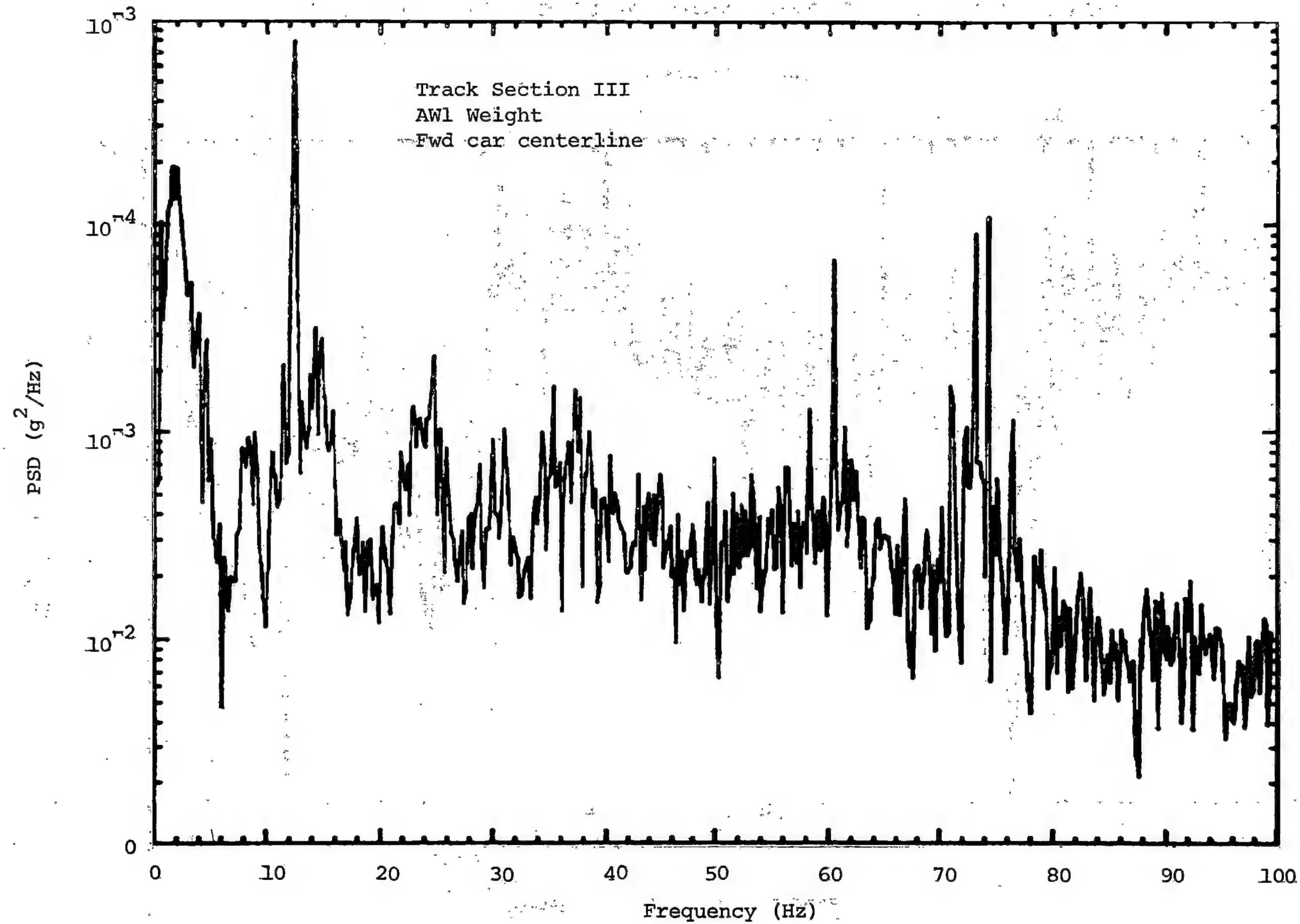


FIGURE 8-35. FORWARD VERTICAL VIBRATION SPECTRA AT 60 MI/H.

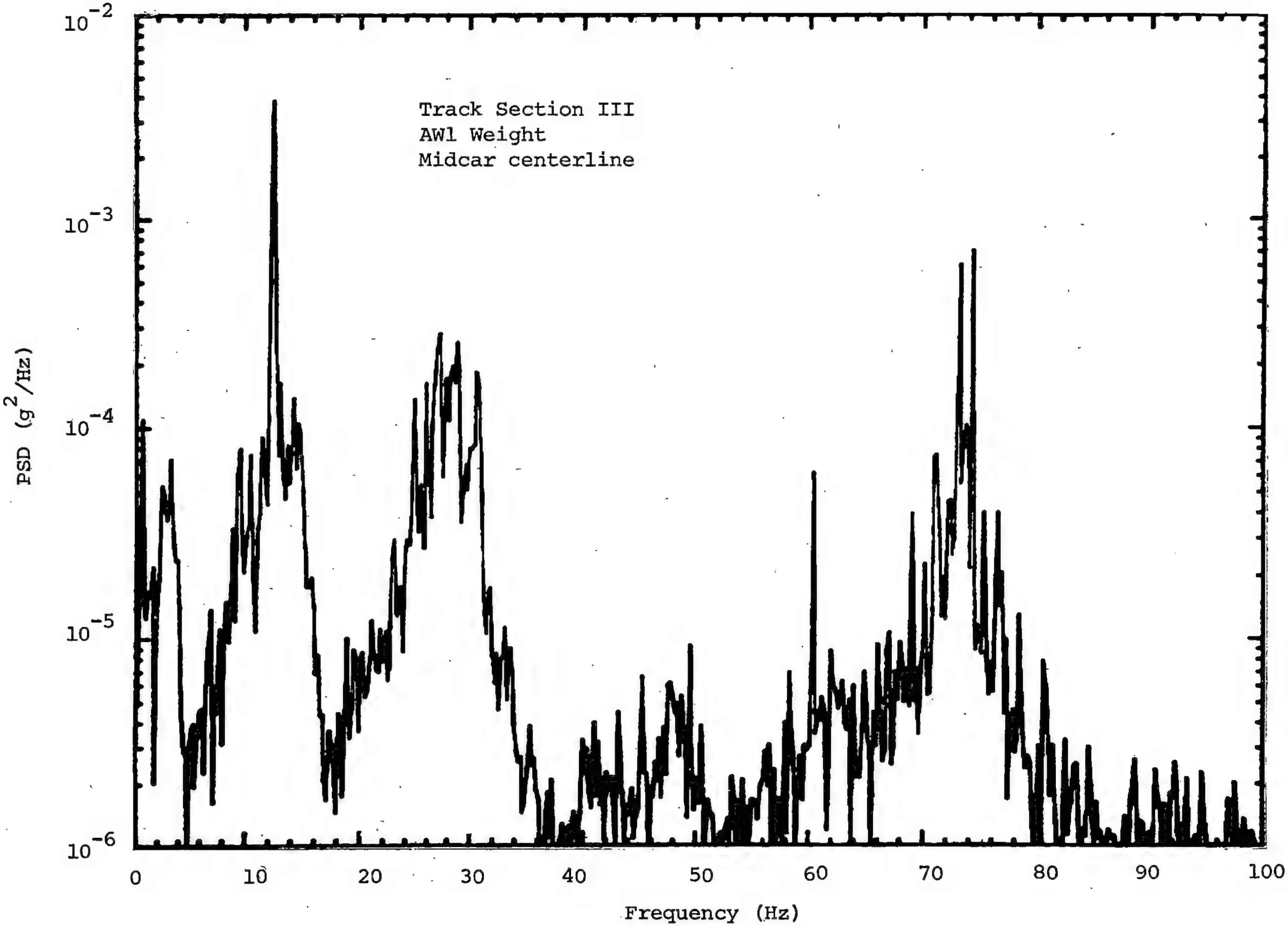


FIGURE 8-36. MIDCAR VERTICAL VIBRATION SPECTRA AT 60 MI/H.

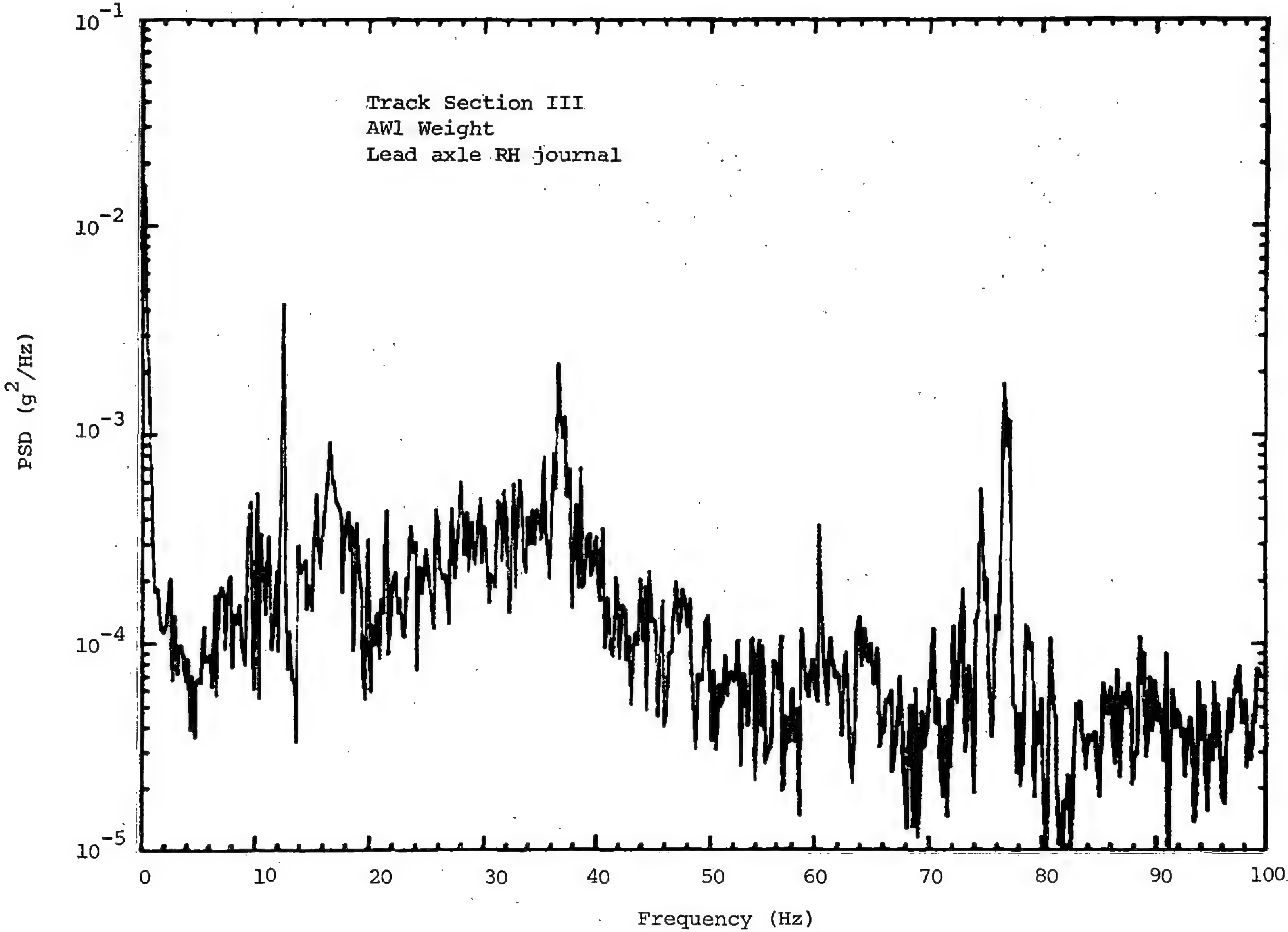


FIGURE 8-37. JOURNAL BEARING LATERAL VIBRATION SPECTRA AT 60 MI/H.

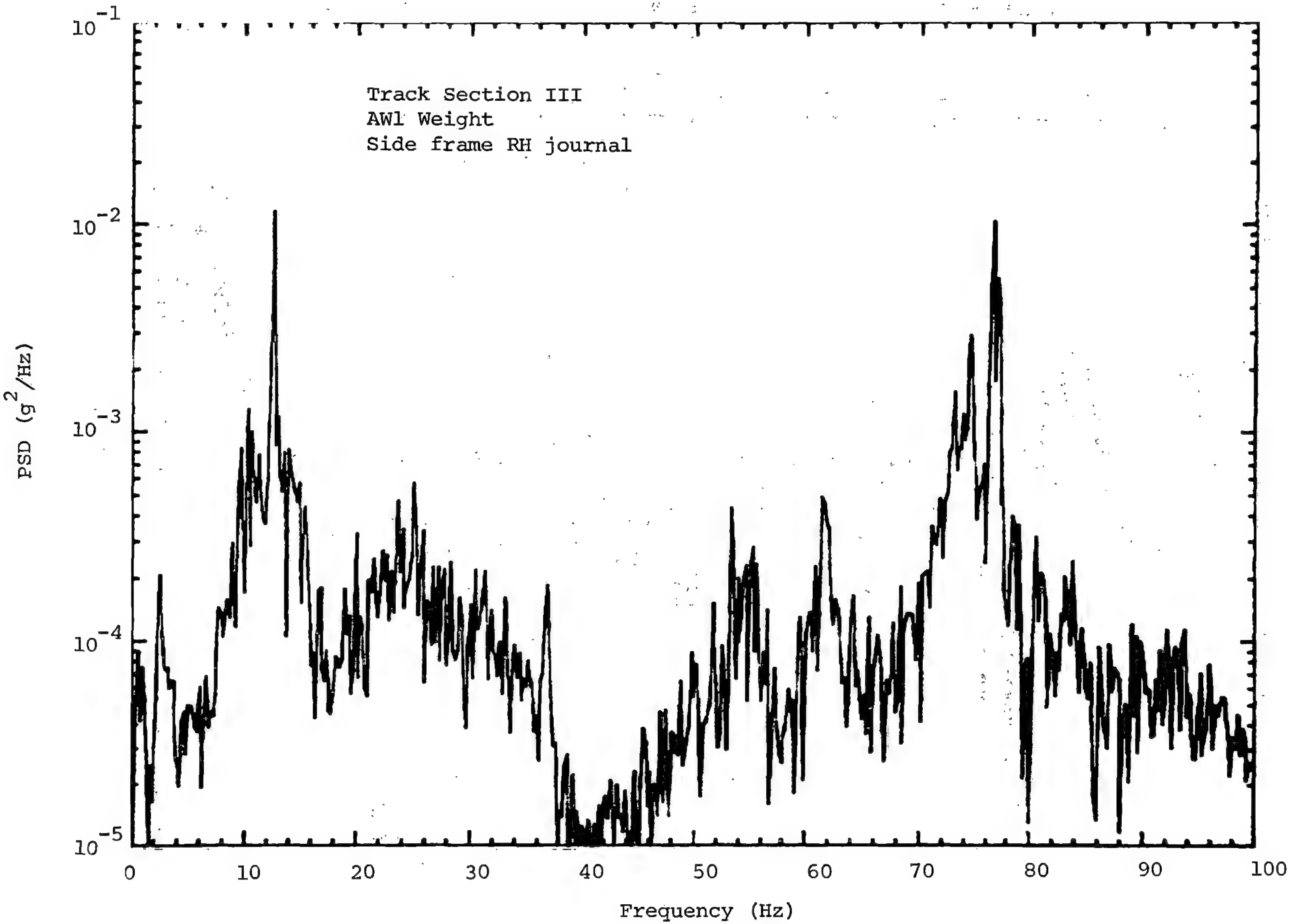


FIGURE 8-38. TRUCK SIDE FRAME LATERAL VIBRATION SPECTRA AT 60 MI/H.

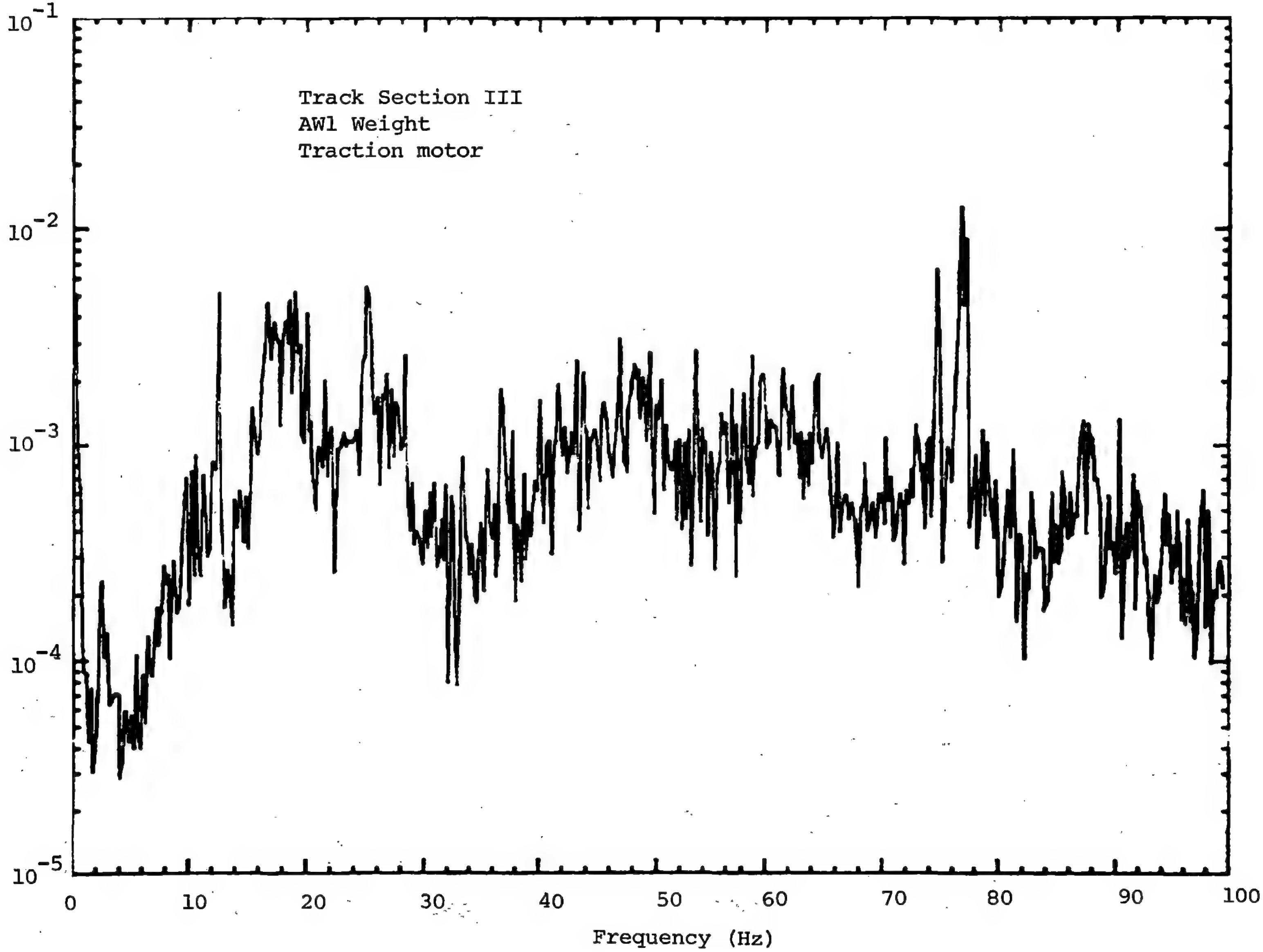


FIGURE 8-39. TRACTION MOTOR LATERAL VIBRATION SPECTRA AT 60 MI/H.

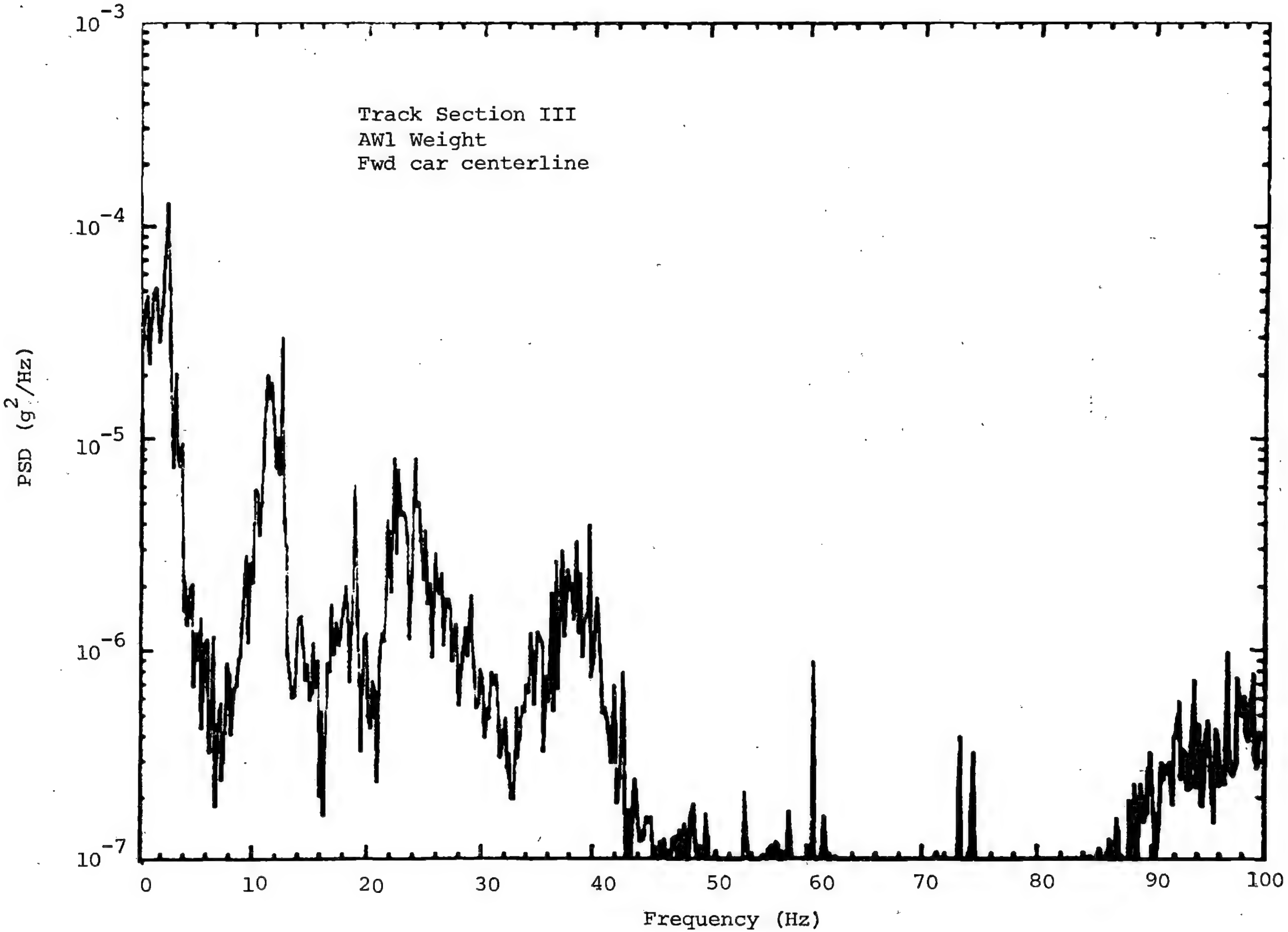


FIGURE 8-40. FORWARD LATERAL VIBRATION SPECTRA AT 60 MI/H.

9.0 SPECIAL ENGINEERING TESTS

At the conclusion of the standardized test portion of the Blue Line test program, MBTA requested that a series of brake shoe and energy conservation tests be conducted for the information of their Program Office. Test planning and procedures were provided by L.T. Klauder and Associates, the consultant engineers for MBTA. Although these tests involved unique procedures, the instrumentation installation, data acquisition, and data processing were performed in accordance with the GVTP.

9.1 BRAKE SHOE TEST

9.1.1 Test Objectives

To evaluate three types of experimental brake shoes for use on transit vehicles: WABCO type 539, Abex type T-176-4, and Griffin Anchor type.

9.1.2 Test Method

Six characteristics were evaluated:

- Brake fade was determined by measuring total stopping distance from speeds of 15, 25, 35, 45, 55, and 65 mi/h, with the brakes at stabilized operating temperatures,

- Brake noise (squeal) was measured during each stop with hand-held sound meters. In addition to the basic configurations, the effect of isolating the brake shoes from the brake actuator with a rubber pad (shim) was also evaluated,

- Thermal characteristics were measured by the use of two thermocouples located on two different brake shoes,

- Brake shoe wear was evaluated by recording the weight of the brake shoe at the start and end of each test series,

- Wear effect on performance was evaluated by conducting braking tests, first with new brake shoes, then machining the shoes to a half-worn condition and repeating the tests, and

- Effect of car weight on brake shoe performance was evaluated by conducting the tests at weights AW0 and AW3.

The parameters listed below were monitored and recorded.

- Brake shoe temperature. Brake shoe temperatures were monitored on the second axles of both cars (locations 0609-L2 and 0608-R2). Each shoe had one thermocouple embedded and one attached to the side of the shoe. The thermocouple installation was similar to that used for duty cycle testing (section 6.4), with the exception that for duty cycle tests, only

location 0609-L2 was instrumented, as shown in figure 6-24. Ambient temperatures were also monitored and recorded in the area of the brake shoes; details are given in appendix A, section 1.4.

- <u>Noise level outside the car</u>. The sound level meter was mounted on car 0609 on an outside door, 6" below the door threshold.

- <u>Noise level inside the car</u>. The sound level meter was mounted in car 0609 in the guard seat with both crew windows open.

Each brake shoe was measured and weighed at the start and end of each test series. Before any test series was begun, each type of brake shoe was installed and sufficient stops were made using friction-only braking to seat the shoes and ensure 100% contact between the brake shoe and wheel.

The MBTA Blue Line profile, as described in table 6-10 and appendix C, was run using full service blended brakes to stabilize temperatures before the test runs were carried out. The stabilized brake shoe temperatures were recorded and temperature records were maintained for the duration of the test. One test consisted of four runs (two in each direction) for each required speed (10 mi/h increments from 15 to 65 mi/h). The vehicle was accelerated to the target speed, then full service braking was applied to bring the vehicle to a stop. The peak reading of each sound level meter was recorded, along with brake shoe temperatures and stopping distance. The sequence was then repeated using only friction brakes (dynamic brakes disabled). This test sequence was used for car weights AW0 and AW3, with new and half-worn examples of each manufacturer's brake shoes.

Reference noise and stopping distance tests were conducted on the WABCO type 392 brake shoes (original vehicle equipment). These reference data were obtained with the shoes installed in the as-built configuration, and were repeated with a rubber shim bonded to the back of the brake shoe between the brake shoe and the brake actuator; the shim was intended to reduce noise transmission to the trucks.

Instrumentation used for the brake shoe evaluation tests is described in appendix A, section 1.4, and the test log summary is given in appendix C.

9.1.3 <u>Test Results</u>

The performance of the four types of brake shoe is discussed in the following paragraphs.

a. <u>Brake fade comparison</u>. Stopping distance was used as an indication of brake fade; the results are illustrated in figures 9-1 through 9-5. Figure 9-1 shows the relationship between initial speed and stopping distance for the four brake shoe types at AW0 vehicle weight. The figure shows the blended brake mode in which friction braking comes into action on braking initiation and below a speed of 15 mi/h, when dynamic braking effort ceases. There was little or no detectable fade in the blended brake mode; furthermore, there is no significant difference in the curves for the three experimental shoe types and the production WABCO 392 brake shoe, with or without shims. (In the blended braking mode, the friction

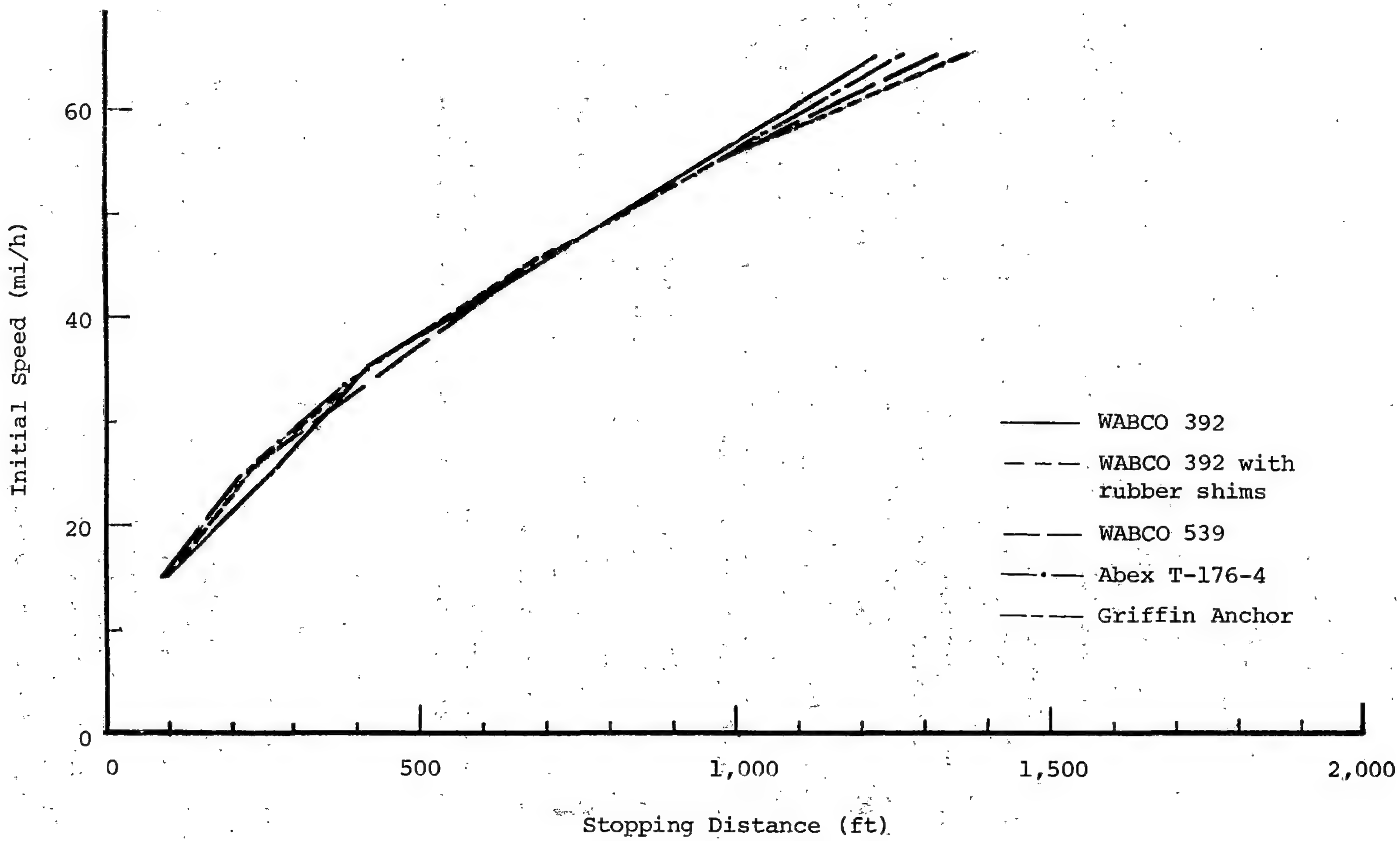


FIGURE 9-1. COMPARISON OF SHOE TYPES, FULL SERVICE BLENDED BRAKE.

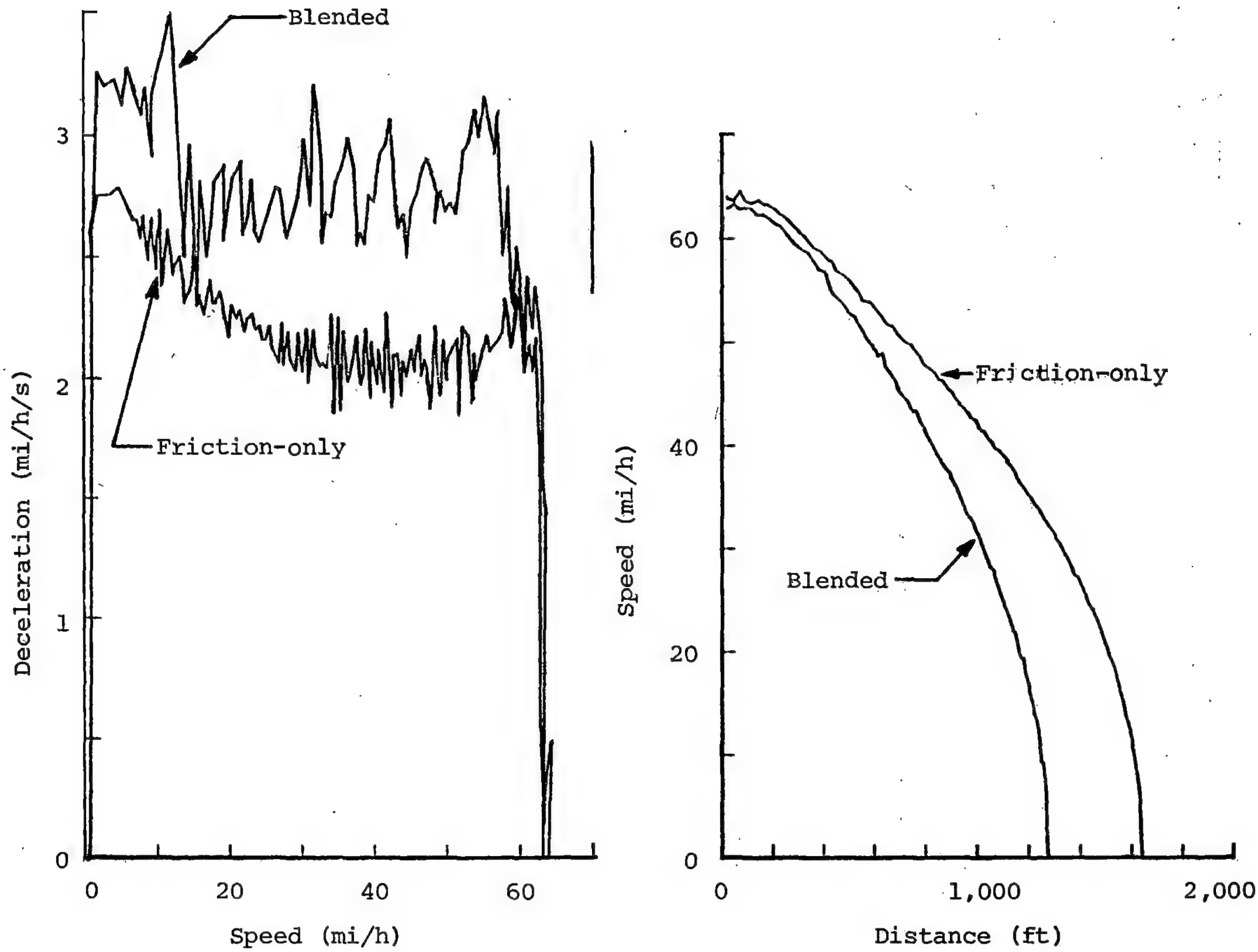


FIGURE 9-2. COMPARISON OF FRICTION-ONLY AND BLENDED BRAKE, WABCO 539 SHOES.

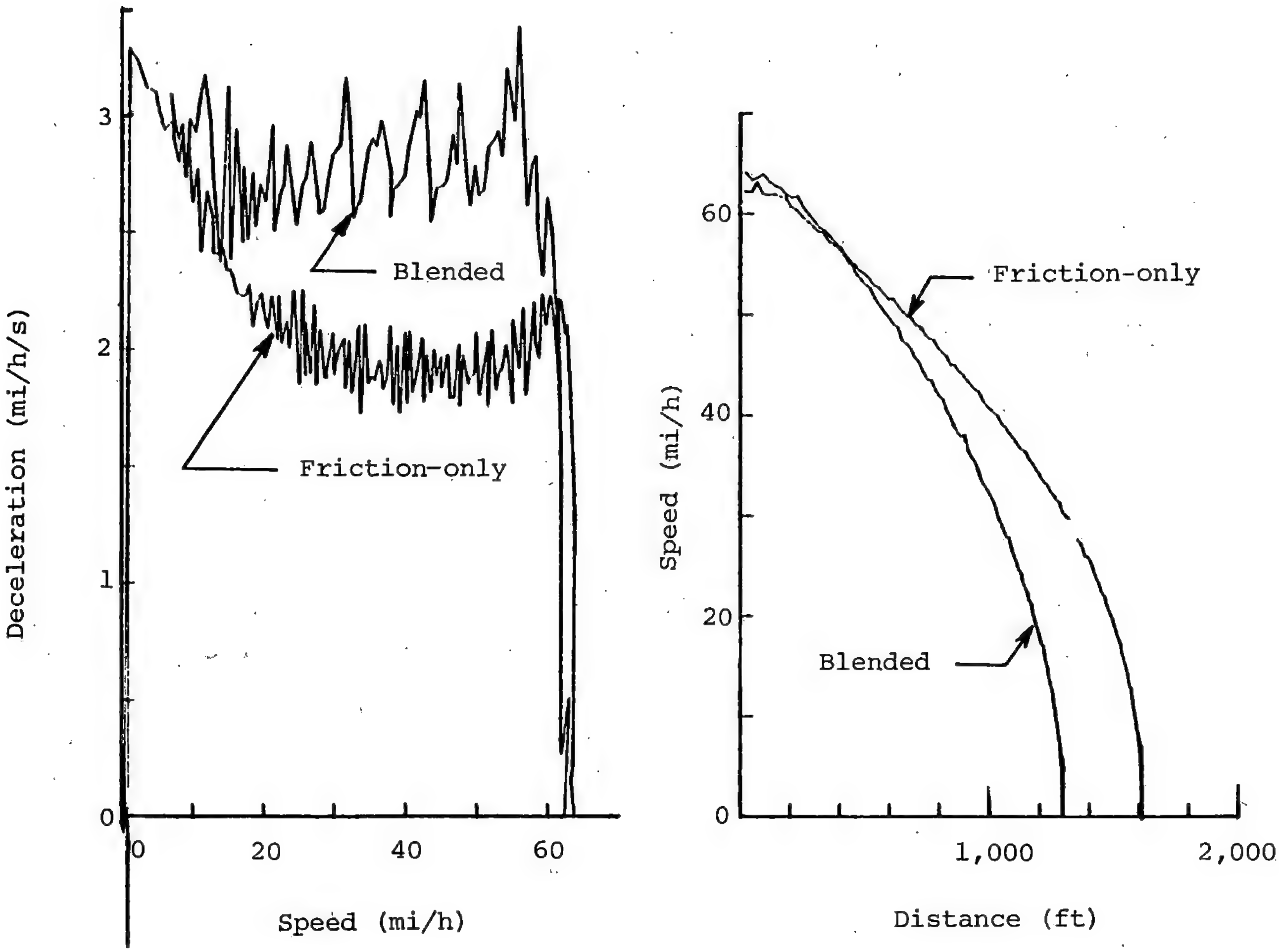


FIGURE 9-3. COMPARISON OF FRICTION-ONLY AND BLENDED BRAKE, ABEX T-176-4 SHOES.

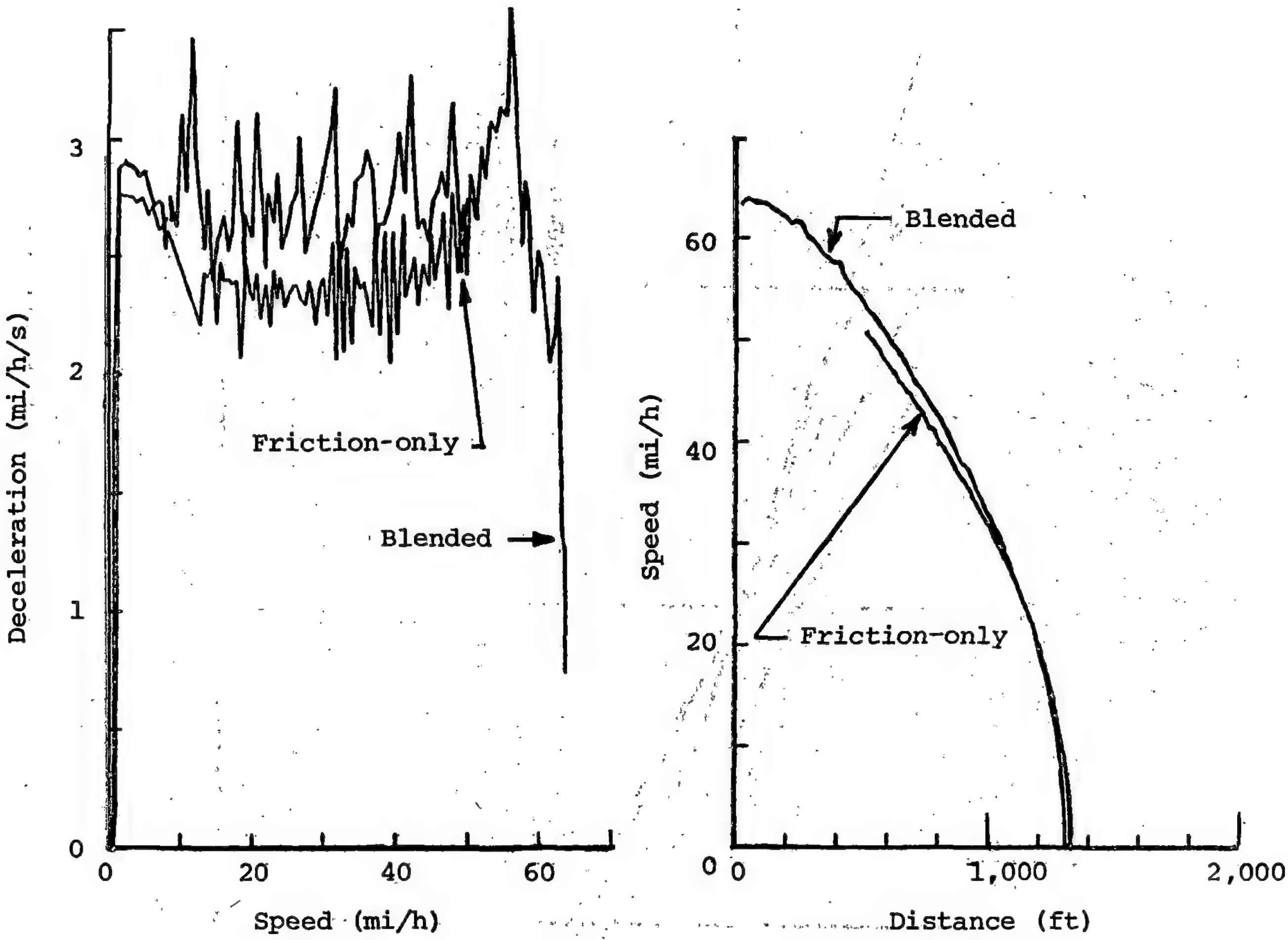


FIGURE 9-4. COMPARISON OF FRICTION-ONLY AND BLENDED BRAKE, GRIFFIN ANCHOR SHOES.

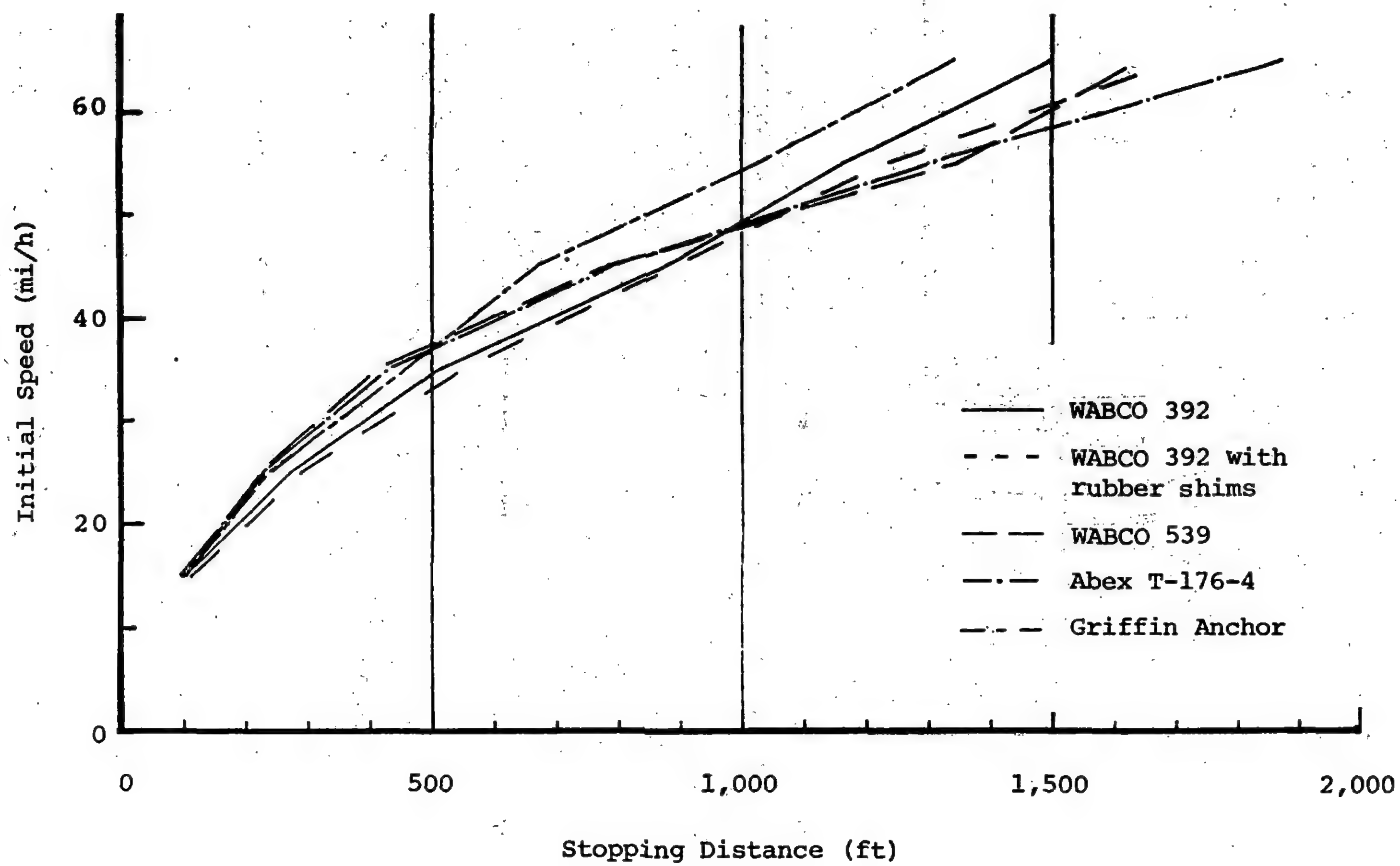


FIGURE 9-5. COMPARISON OF SHOE TYPES, FRICTION-ONLY BRAKE.

brakes were lightly loaded and could have been expected to show little brake fade effect.)

Figures 9-2, 9-3, and 9-4 show a comparison of friction-only and blended brake mode deceleration rates and stopping distances for the three experimental brake shoes at AW3 vehicle weight. Initial speeds were 65 mi/h. The speed/distance plots for the WABCO 539 and Abex T-176-4 shoes with friction-only braking show stopping distances on the order of 300-320 ft greater than for blended braking. The deceleration rates are correspondingly 0.5 mi/h/s less over the upper speed range. The Griffin Anchor shoes were able to stop the vehicle in the same distance as in the blended brake mode. A comparison of initial speed vs. stopping distance in the friction-only brake mode for the three experimental shoes and the original equipment shoes is presented in figure 9-5. This comparison shows that the WABCO 539 and Abex T-176-4 shoes require longer stopping distances than the original vehicle equipment at speeds over 50 mi/h, but have equal or slightly better performance below this speed (i.e., in the normal operating speed range of the MBTA Blue Line car). The Griffin Anchor shoes have better stopping distance performance than the standard brake shoes thoughout the speed range.

It is conceivable that the differences in stopping distances between shoes could have been due to inherent differences in their coefficients of friction. "Tailoring" the brake actuator pressures to suit individual brake shoe characteristics could restore braking performance to the specification requirement of 2.75 mi/h/s for all shoes at the higher speeds. In order to adequately conduct a more rigorous characterizition of each shoe's fade properties, further tests are required, varying brake actuator pressure and comparing hot brake shoe performance to cold.

All the brake shoes tested have adequate brake fade properties for revenue service in the normal blended braking mode. Over a revenue service profile simulating the Blue Line, stopping distances were comparable to blended braking when operated in a friction-only mode at speeds up to 40 mi/h.

Figures 9-6 through 9-8 compare the speed/deceleration and speed/distance characteristics for new and half-worn experimental shoes in the friction-only mode. There is close agreement in the characterisitics between WABCO and Abex new and half-worn shoes, with some improvement in the deceleration rate in the case of Griffin half-worn shoes over the new.

b. Noise (squeal) comparison. Noise comparisons were accomplished concurrently with brake fade testing. Noise data were recorded for full service braking tests in blended and friction-only modes, from initial speeds of 65, 55, 45, 35, 25, and 15 mi/h.

Brake shoe noise was sensed and displayed by two noise meters, one mounted inside the car opposite the motorman's cab, and one outside at the right front door at approximately ear level. The readings were A-weighted and the maximum meter deflection, on slow response, was manually recorded for each run. Each test was repeated to yield two sets

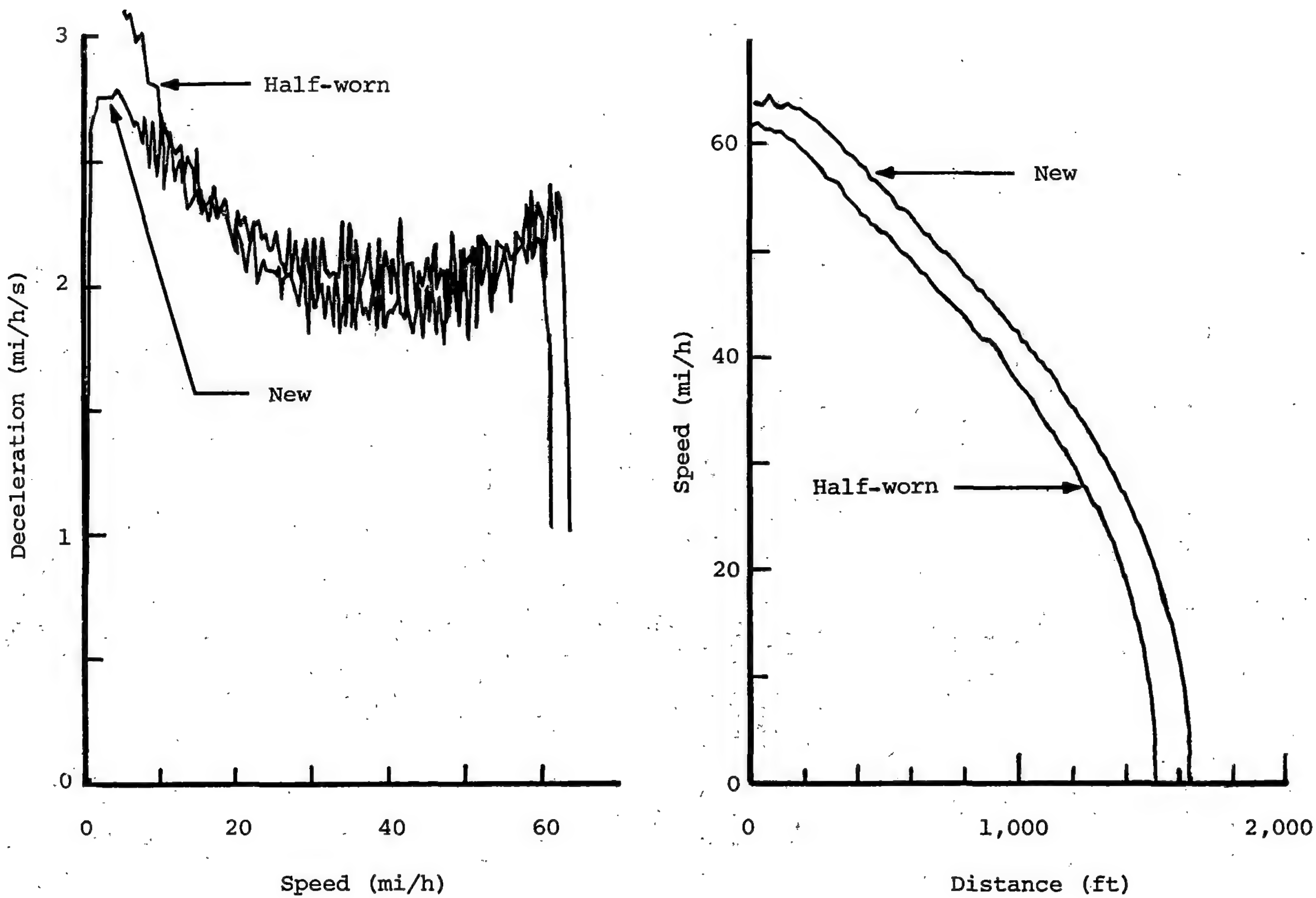


FIGURE 9-6. PERFORMANCE CHARACTERISTICS FOR NEW AND HALF-WORN SHOES, WABCO 539.

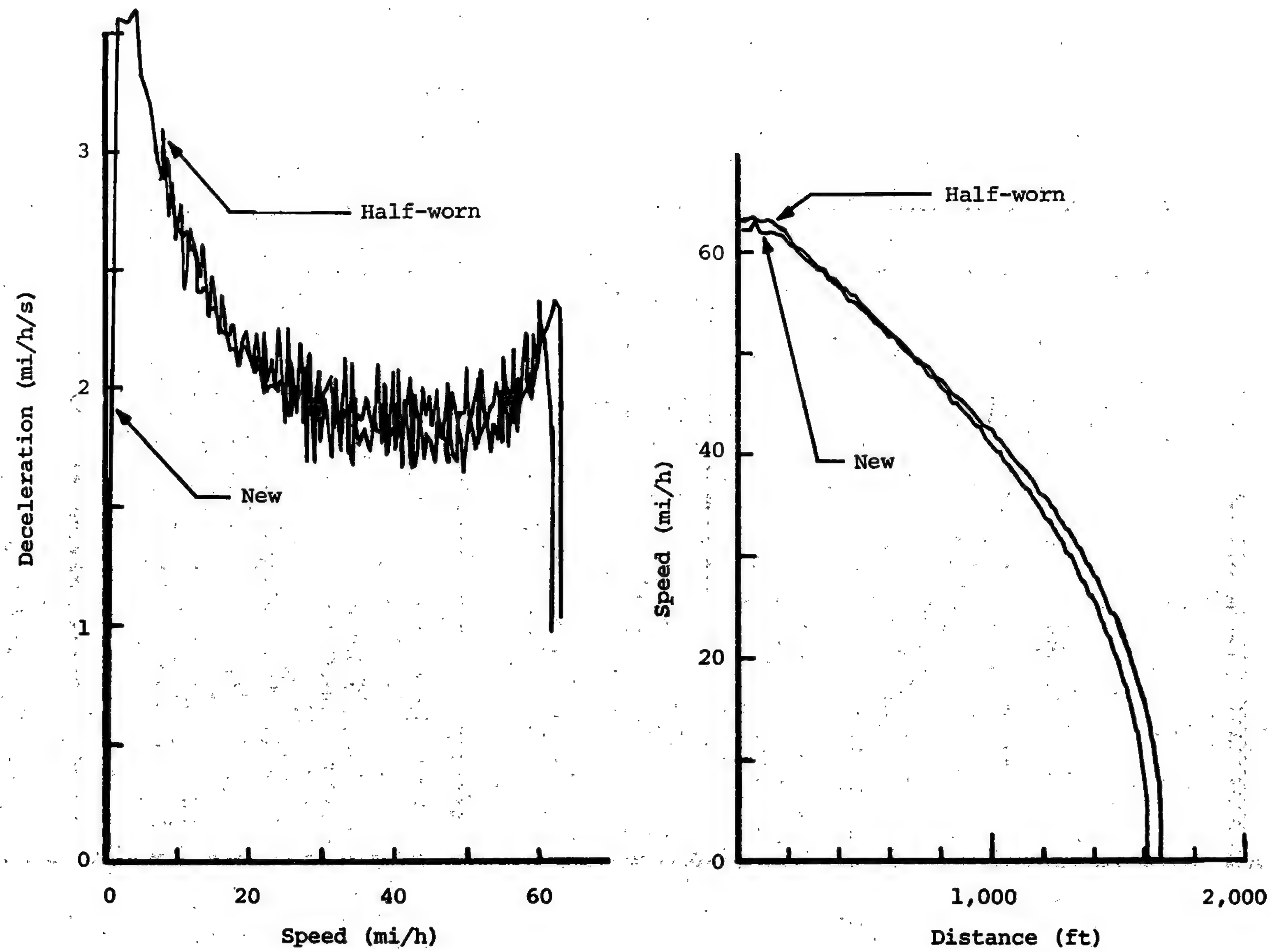


FIGURE 9-7. PERFORMANCE CHARACTERISTICS FOR NEW AND HALF-WORN SHOES, ABEX T-176-4.

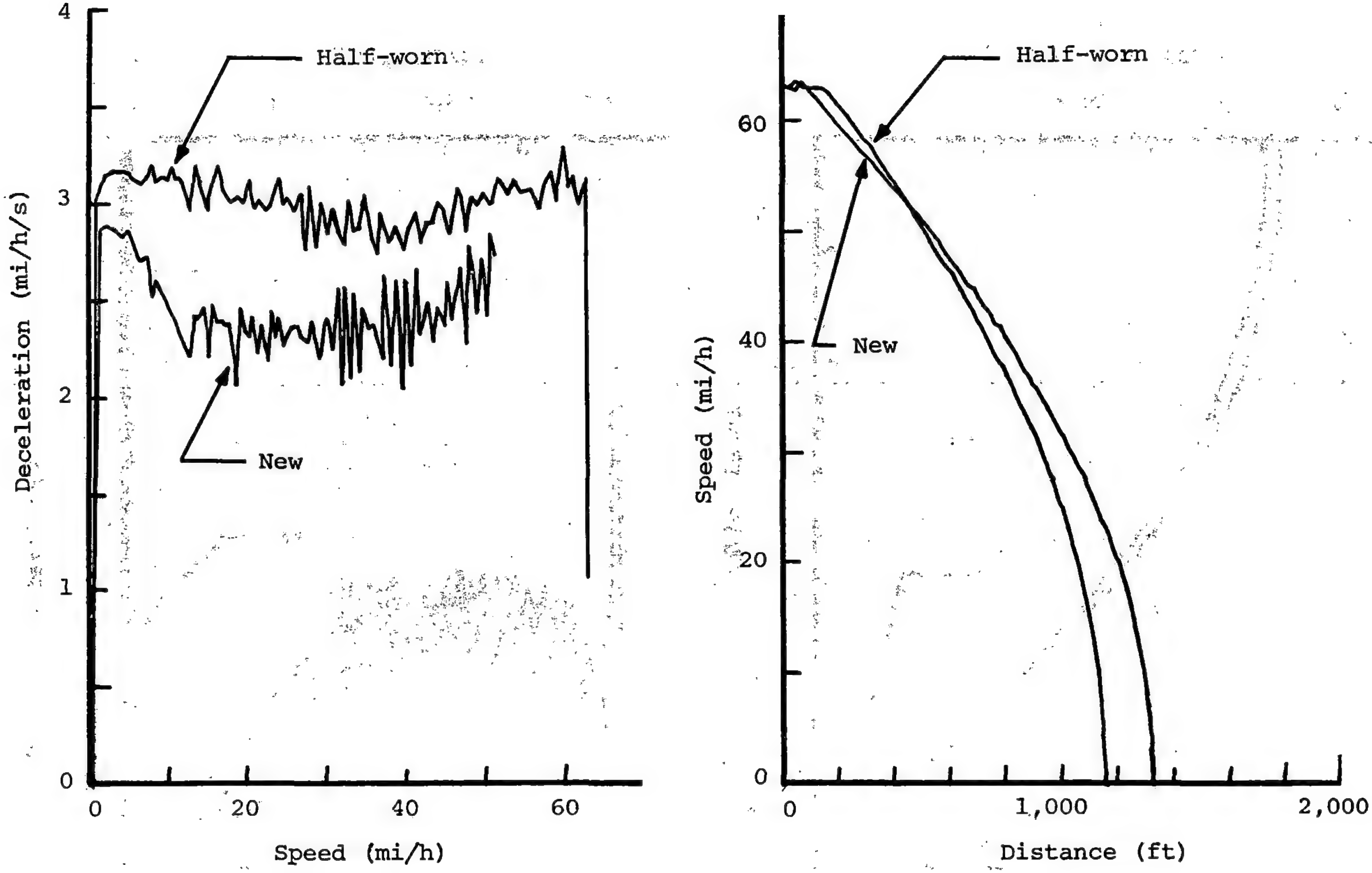


FIGURE 9-8. PERFORMANCE CHARACTERISTICS FOR NEW AND HALF-WORN SHOES, GRIFFIN ANCHOR.

of readings each for CW and CCW stops. The data were merged from these repeat runs for analysis; for a given pair of repeated readings, they were first converted to sound pressure ratios, averaged, and then converted to a single dBA reading.

The maximum noise levels recorded for the WABCO 392 brake shoes (as-built equipment) were used for reference; these are shown in figure 9-9 (blended brake) and 9-10 (friction brakes only) for AW0 weight. Figure 9-9 shows that noise levels varied between 102-115 dBA for the inside microphone, but were lower (between 67-85 dBA) for the outside microphone in the blended brake mode. As was expected, noise levels remained generally constant with speed in the blended brake mode, since regardless of initial speed, friction brakes were operative only below about 15 mi/h.

In the friction-only brake mode for the WABCO 392 shoes (figure 9-10), the noise levels at low speeds were similar to the blended braking mode, but decreased significantly with increasing initial braking speed. For example, at 55 mi/h initial speed, the inside peak noise levels were 109-115 dBA for blended braking, and fell to 80-89 dBA in the friction-only mode. It appears that brake shoe temperatures were increased due to the prolonged brake application at the higher speeds and that brake squeal is an inverse function of brake shoe temperature; regardless of the initial braking speed, all brake squeal was produced at low speeds.

c. Noise level with rubber shims. A comparison of production WABCO 392 brake shoe noise levels in the blended brake mode (figures 9-9 and 9-11, respectively) shows no significant trends due to the shims; the overall range of noise level remains the same for both inside and outside car measurements.

d. Experimental shoe, noise levels. The noise level data for the three experimental shoes showed large variations. WABCO 539 noise levels were comparable to the reference shoes, but Abex T-176-4 and Griffin Anchor had lower levels. Abex T-176-4 noise levels were all below 50 dBA. Figure 9-12 summarizes sound levels inside and outside the vehicle in the blended brake mode, for the three experimental shoe types. Here, data at all speeds in both directions of operation and at all weights have been averaged by sound pressure level. The noise levels for the experimental shoes are all below 111 dBA, and are less than or comparable to the reference shoes.

Noise levels inside the car were significantly higher than outside. This may be a function of local microphone location and influenced by the fact that the test was specified with both crew windows open.

Noise levels for the three experimental brake shoes as a function of brake initiation speed (AW0 weight, blended brake) are shown in figures 9-13 through 9-15. About 20 dBA difference in noise level is apparent between CW and CCW runs, for both inside and outside microphones.

e. New and half-worn shoe, noise levels. The shoes were machined to the half-worn level for evaluation. Figures 9-16 (WABCO 539), 9-17 (Abex T-176-4), and 9-18 (Griffin Anchor) show noise levels for half-worn shoes

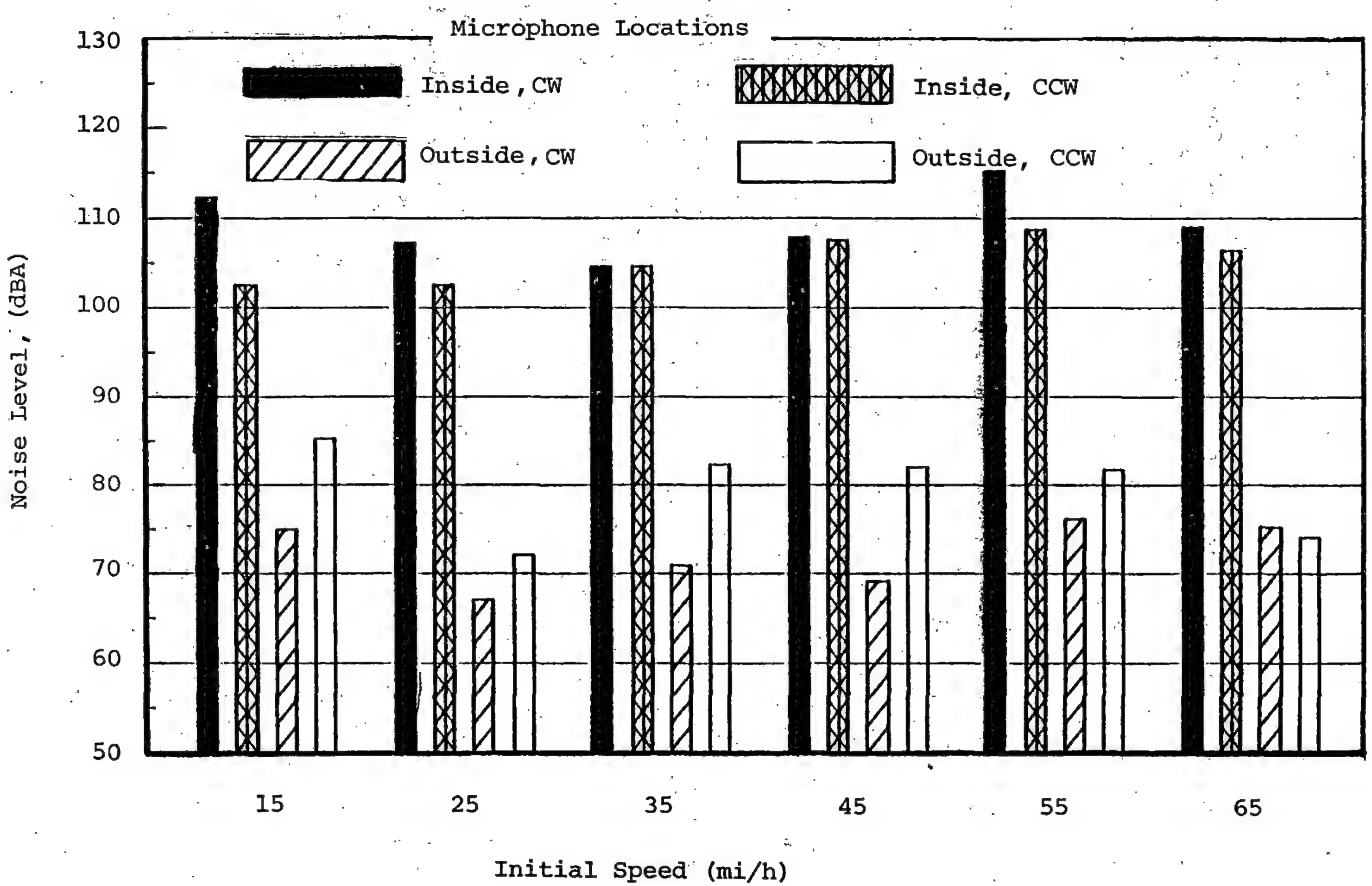


FIGURE 9-9. BLENDED BRAKING NOISE LEVELS, PRODUCTION WABCO 392 SHOES.

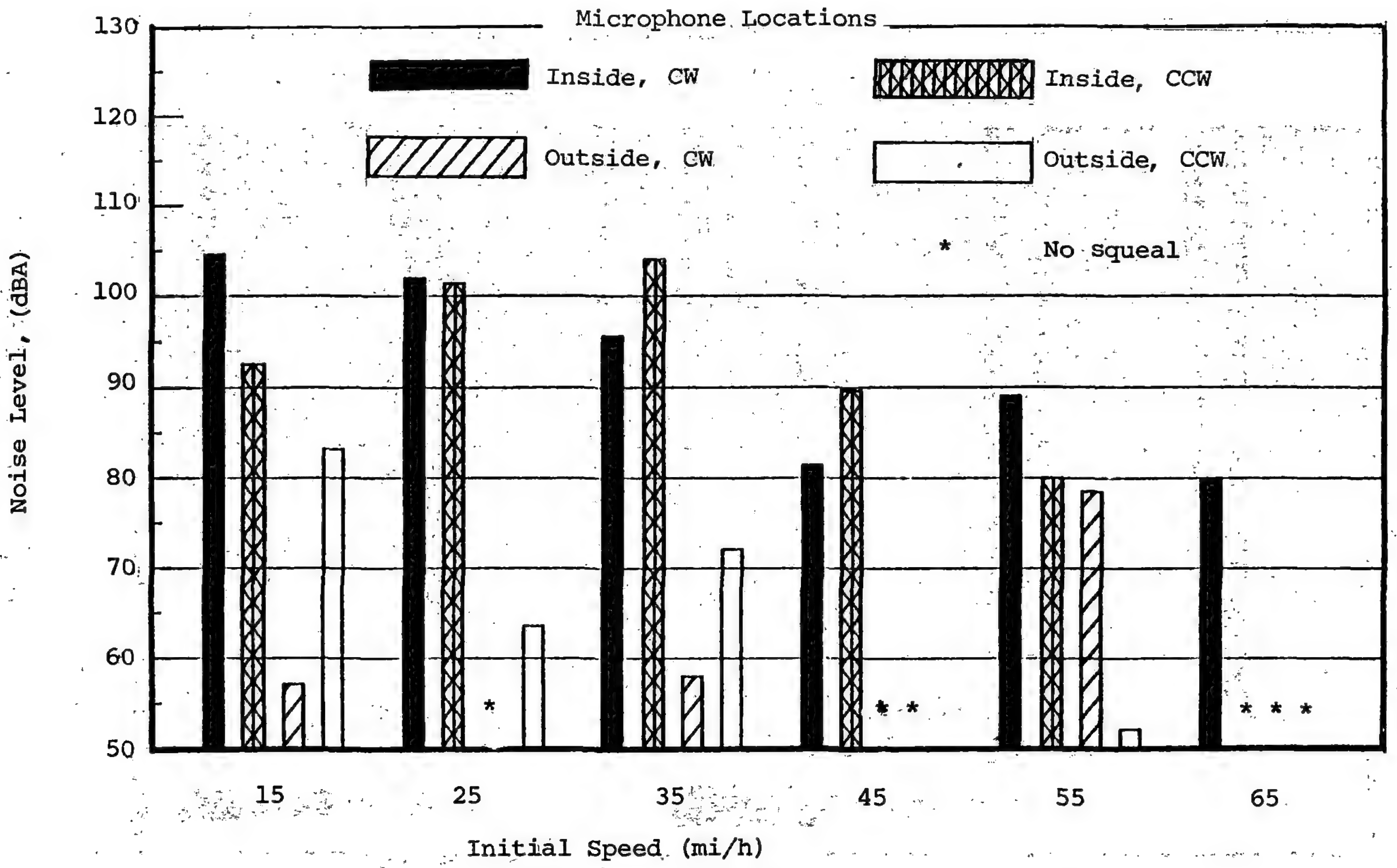


FIGURE 9-10. FRICTION BRAKING NOISE LEVELS, PRODUCTION WABCO 392 SHOES.

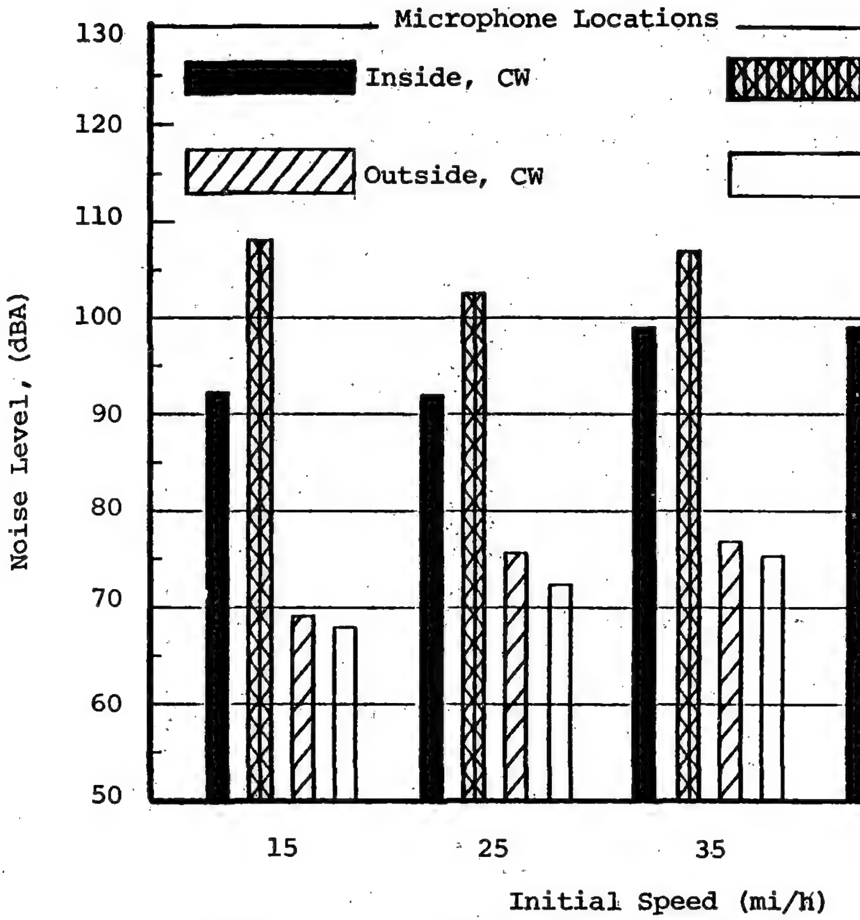
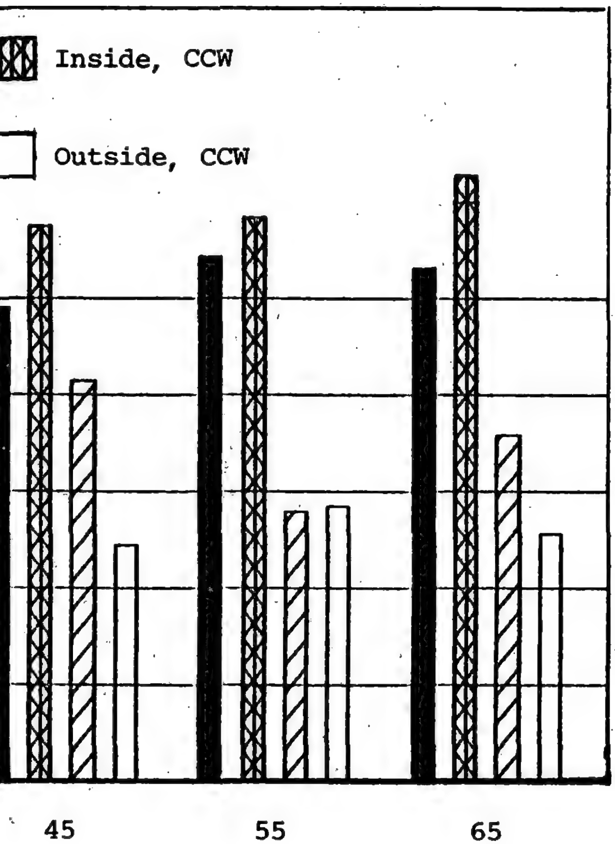


FIGURE 9-11. BLENDED BRAKING NOISE LEVELS,



PRODUCTION WABCO 392 SHOES WITH SHIMS.

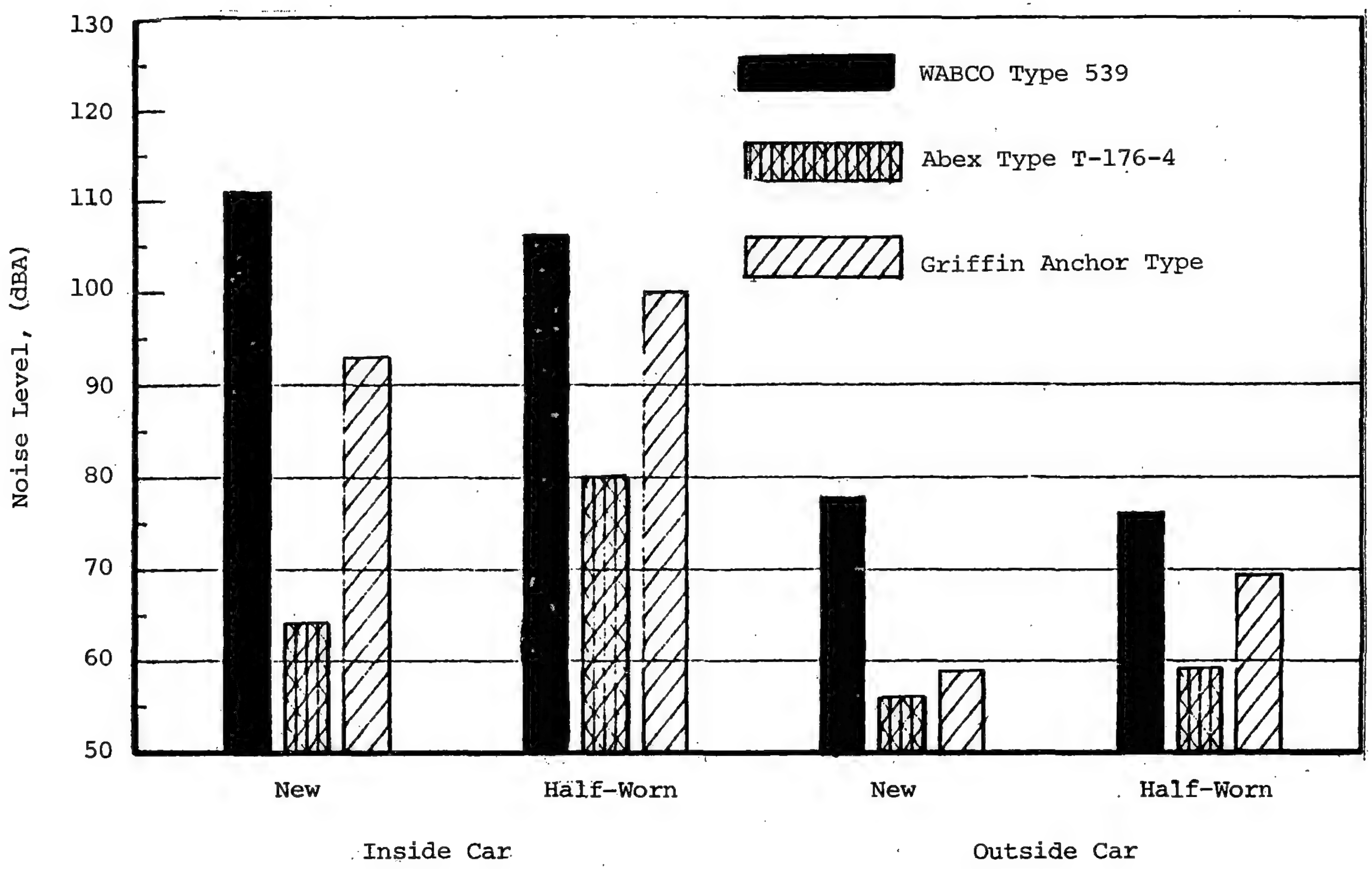


FIGURE 9-12. SUMMARY OF BLENDED BRAKING NOISE LEVELS.

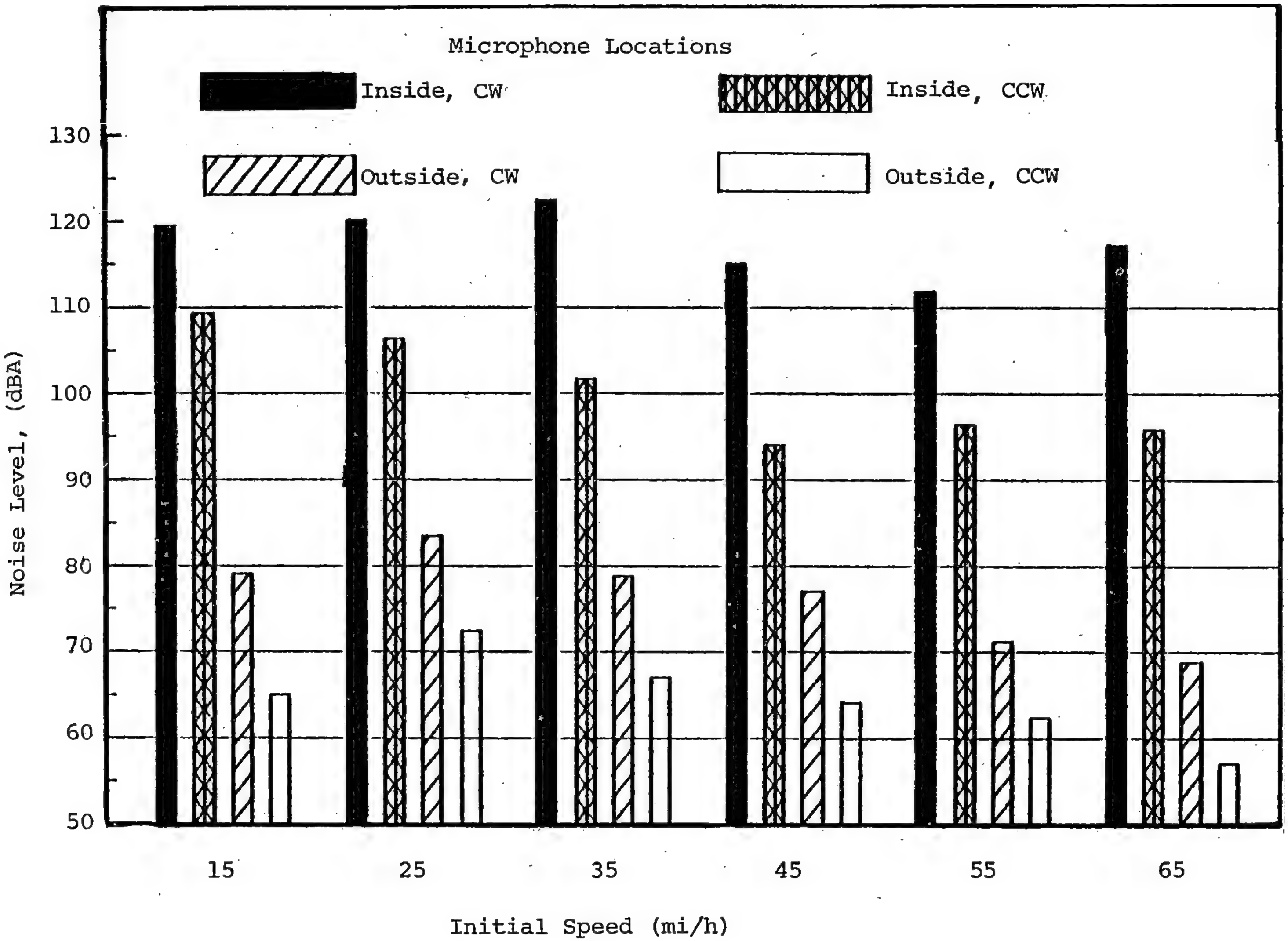


FIGURE 9-13. BLENDED BRAKING NOISE LEVELS, WABCO 539 (AW0 WEIGHT).

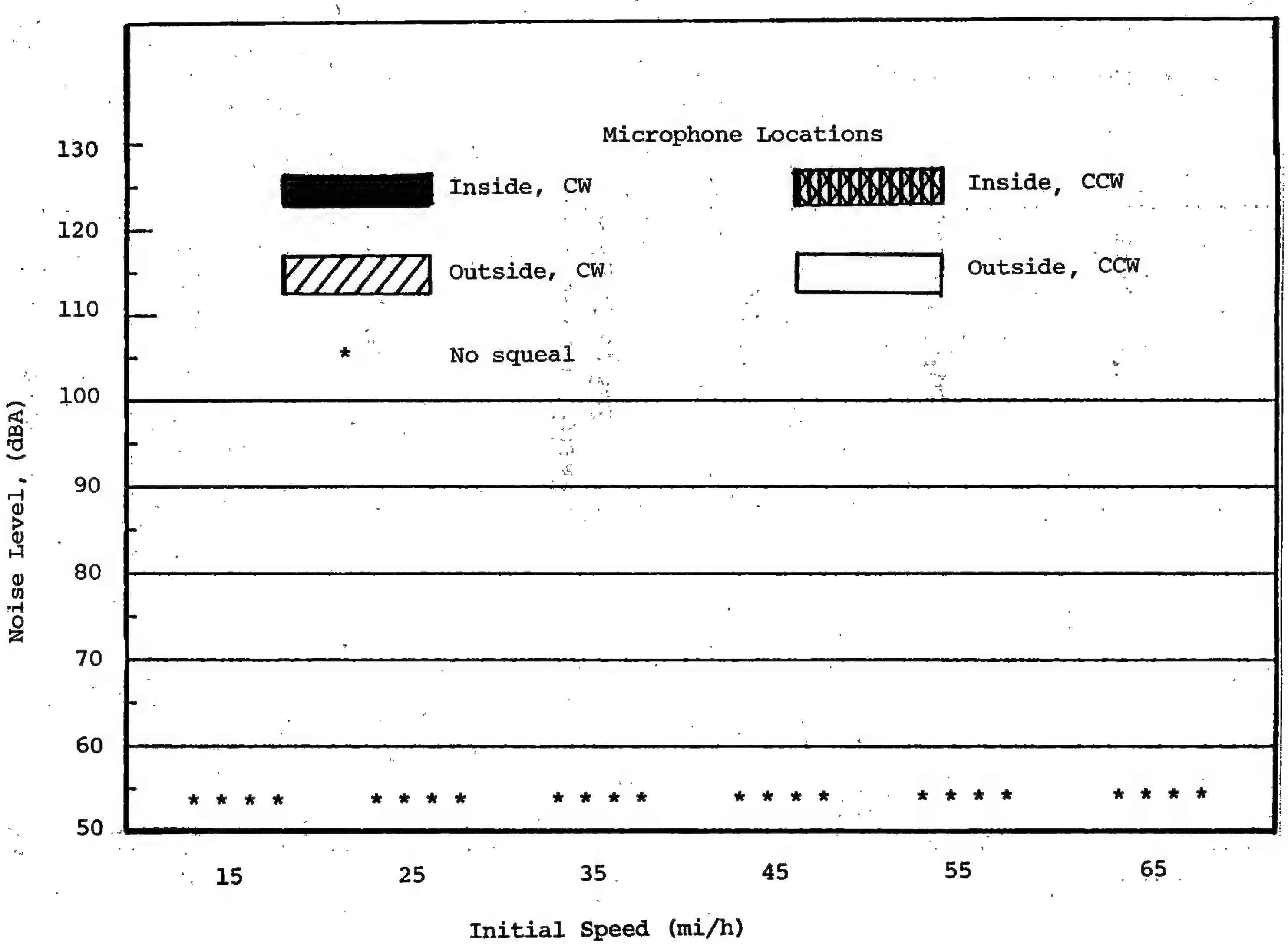


FIGURE 9-14. BLENDED BRAKING NOISE LEVELS, ABEX T-176-4 (AW0 WEIGHT).

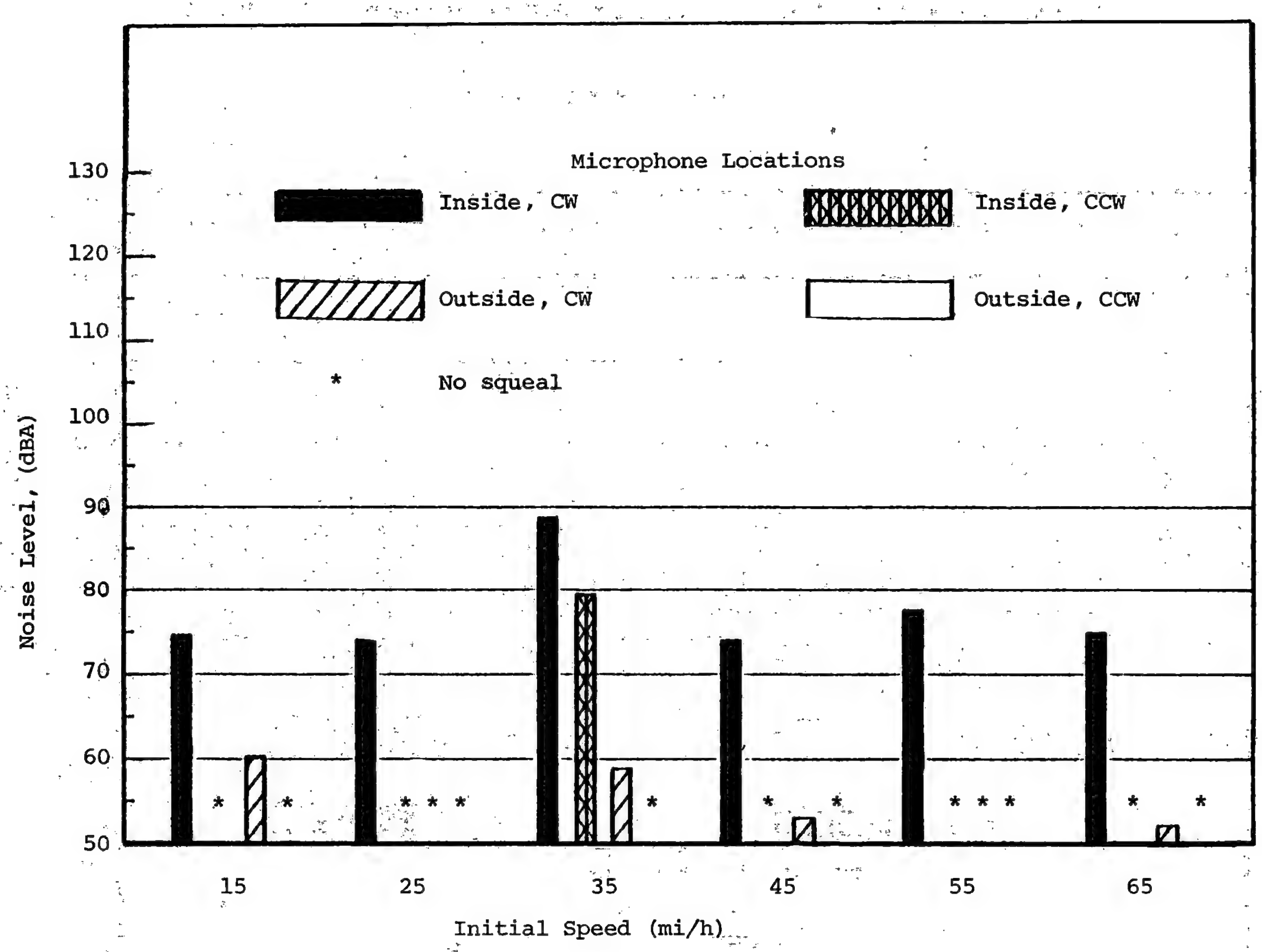


FIGURE 9-15. BLENDED BRAKING NOISE LEVELS, GRIFFIN ANCHOR (AW0 WEIGHT).

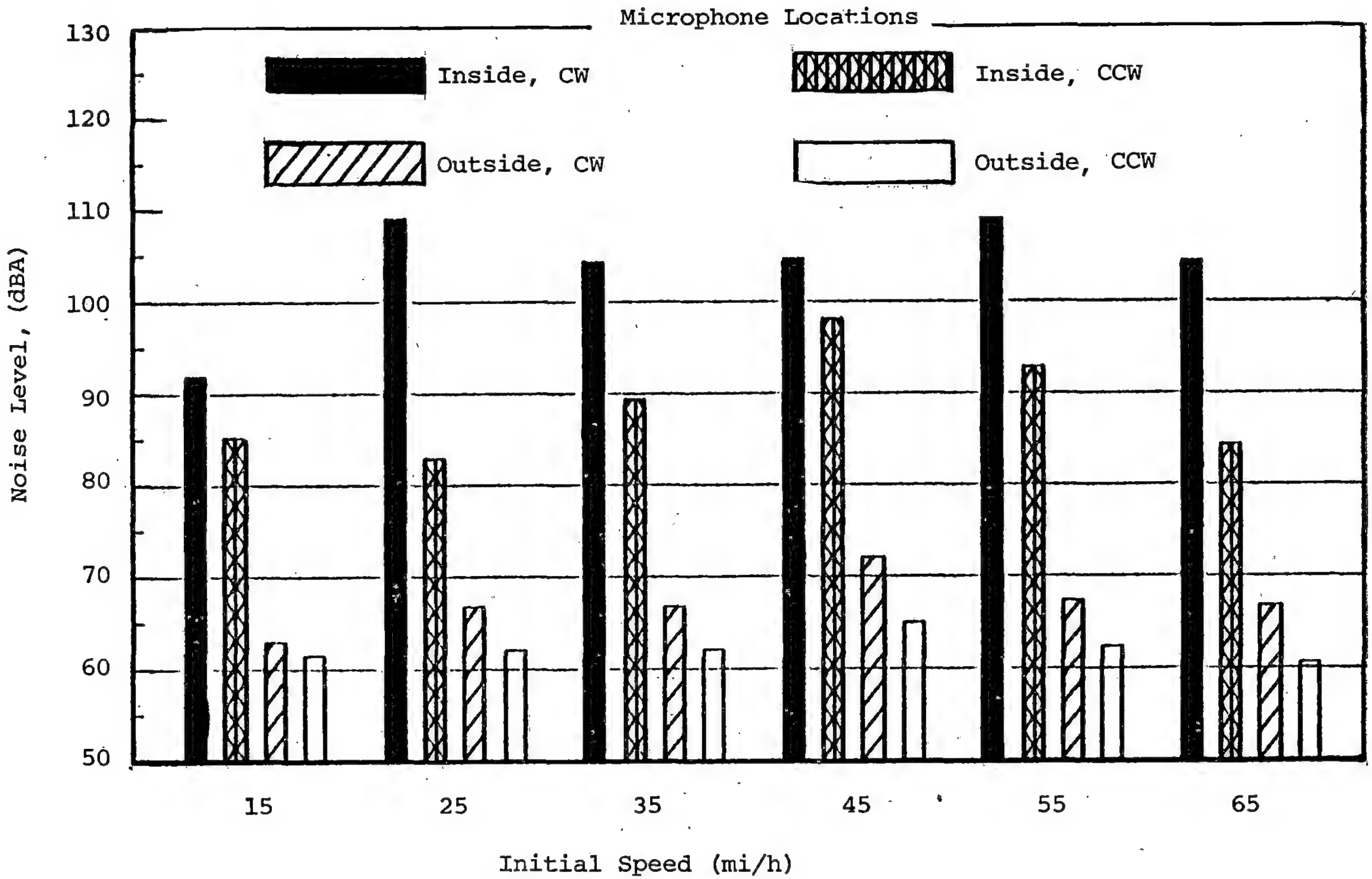


FIGURE 9-16. BLENDED BRAKING NOISE LEVELS, WABCO 539, (HALF-WORN).

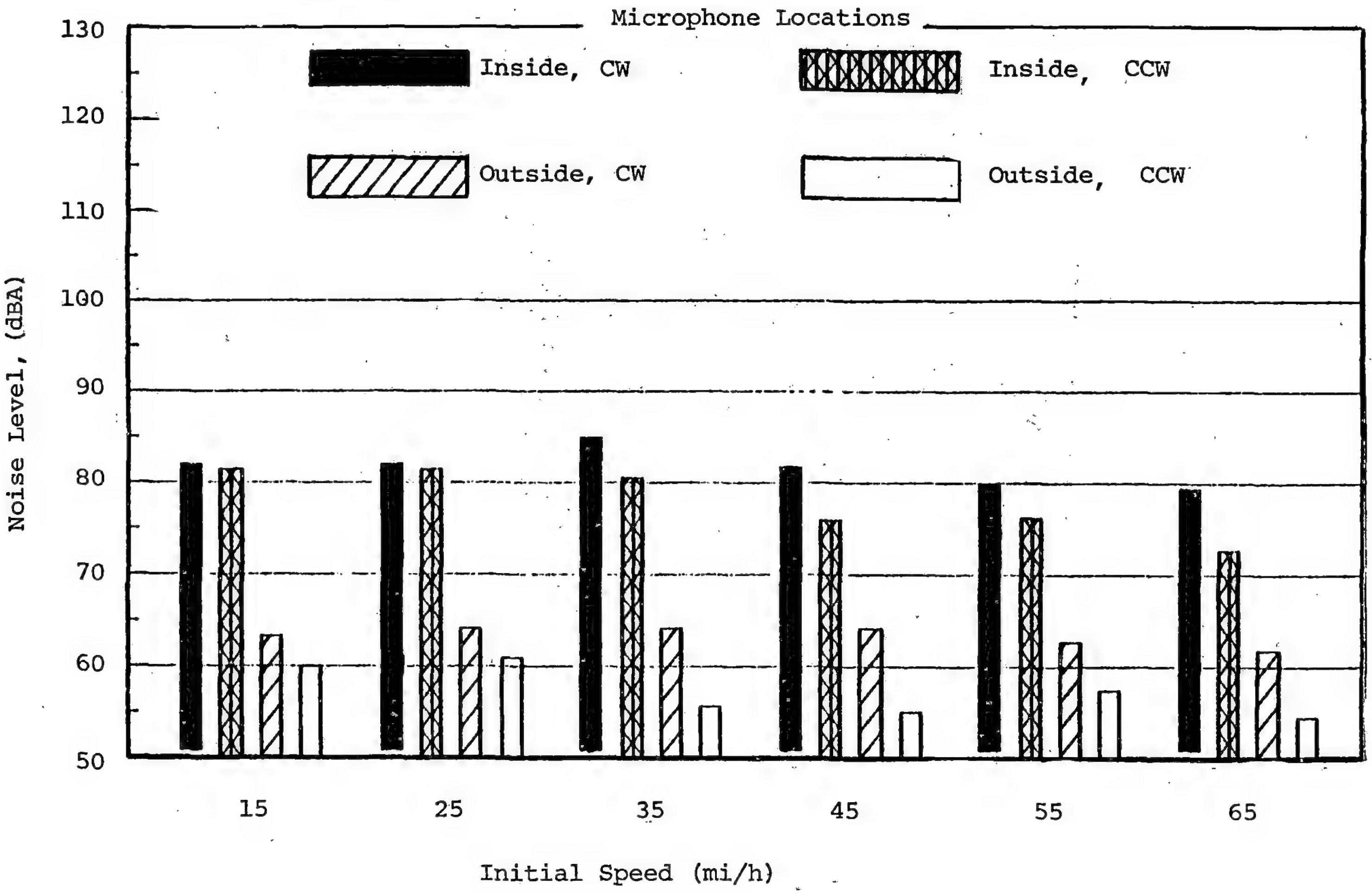


FIGURE 9-17. BLENDED BRAKING NOISE LEVELS, ABEX T-176-4 (HALF-WORN).

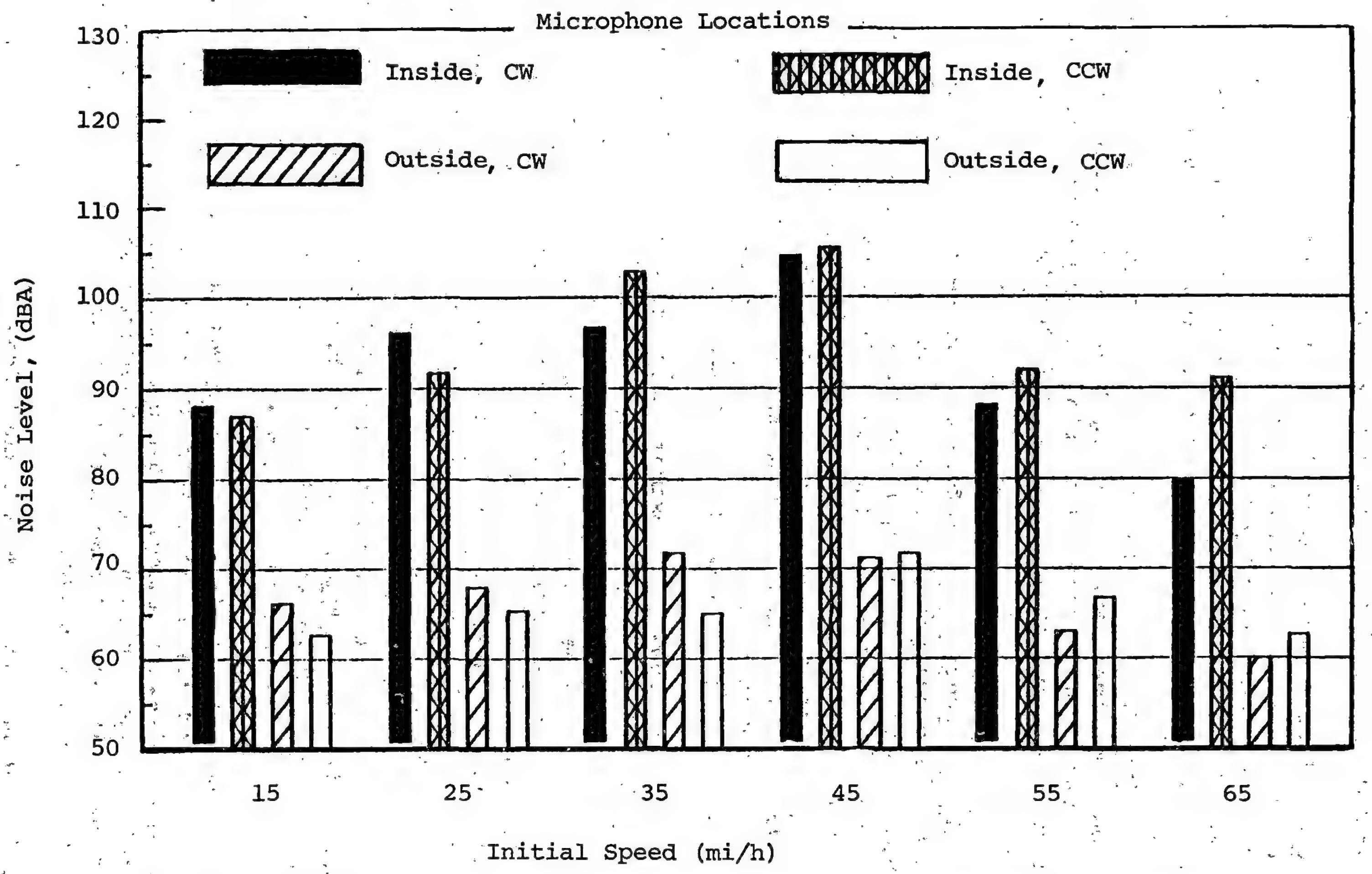


FIGURE 9-18. BLENDED BRAKING NOISE LEVELS, GRIFFIN ANCHOR (HALF-WORN).

in the blended brake mode. There was a slight reduction of noise level when compared to new shoes, possibly caused by operating at a higher temperature due to their lower thermal capacity.

f. Vehicle Weight Effects. Because energy dissipated by the brake system is a function of vehicle mass and the difference between the AW0 and AW3 weights was small in proportion to the total, it was not expected that car weight would have a strong influence on brake noise. There was no consistent trend in noise level between tests at AW0 and AW3 car weights.

g. Braking Mode Effects. Figure 9-19 shows a summary of noise levels inside and outside the vehicle averaged by sound pressure level for the friction-only brake mode. Comparison to figure 9-12 (blended brake mode) indicates a trend toward lower noise levels in the friction-only brake mode.

h. Thermal characteristics. Before each brake testing period was started, a simulated revenue profile run was conducted to bring the brake shoes to a stable temperature. During brake testing, temperature of the brake shoes followed a rise-and-fall sequence. These temperature fluctuations were dependent on time between runs, ambient conditions, speed, etc. Analysis of the maximum temperature values is difficult, because each value is dependent on the maximum temperature of the preceding run. However, the values do permit some degree of comparison between shoe types because the data were collected under similar conditions.

Table 9-1 shows the maximum temperatures reached for the AW0 blended brake and friction-only braking mode.

In the blended brake mode, only a slight increase in temperature appeared with increased initial speed because dynamic braking retarded the vehicles to approximately 15 mi/h. In the friction-only mode, the maximum temperatures increased with greater initial speed. In all cases the friction-only mode resulted in higher maximum temperatures than did dynamic braking.

The differences in maximum recorded temperatures were slight for the experimental shoe types, with production shoes showing the highest temperatures. This was most apparent in the friction-only mode where they are typically 60°-80°F higher.

It can be seen from table 9-2 that the shoes lost material at similar rates and there was little difference between the material lost on new and half-worn shoes. Because the tests were of short duration (total mileage for each test configuration was less than 150 miles), the wear data do not provide sufficient information to predict wear rate trends in revenue service.

The following points are concluded from the special engineering tests on the environmentally safe brake shoes:

- In comparison with the WABCO 392 production brake shoes, the three experimental brake shoes tested (WABCO 539, Abex T-176-4, and Griffin Anchor) all performed satisfactorily with regard to noise and brake fade at speeds up to 40 mi/h.

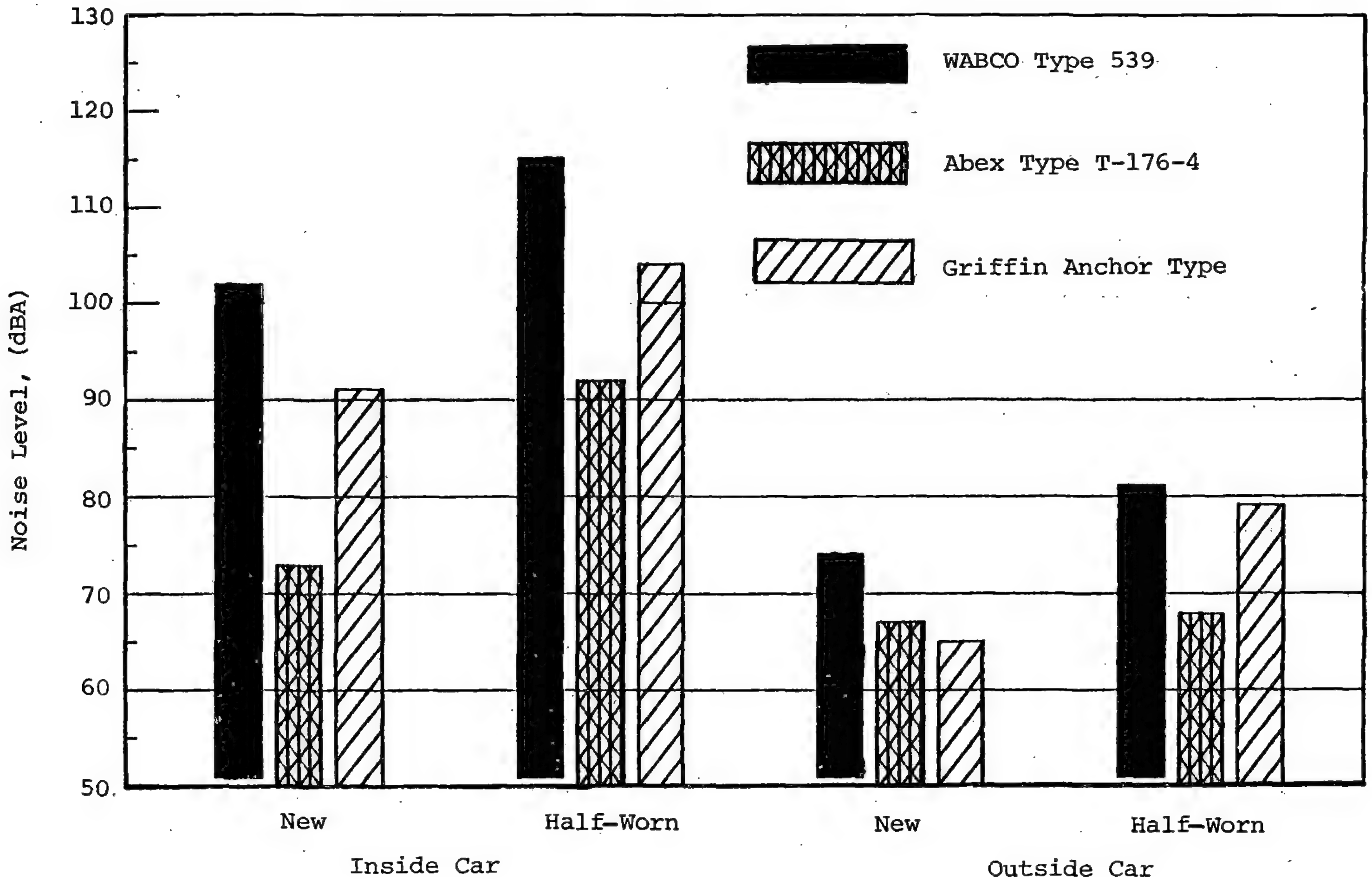


FIGURE 9-19. SUMMARY OF NOISE LEVELS, FRICTION-ONLY BRAKING.

TABLE 9-1. COMPARISON OF MAXIMUM TEMPERATURES FOR BLENDED AND FRICTION-ONLY BRAKING.

Initial Speed (mi/h)	Maximum Temperatures (°F)			
	WABCO W-392 */**	WABCO W-539 */**	Abex T-176-4 */**	Griffin Anchor */**
15	108/205	115/137	90/131	76/128
25	109/203	116/140	91/132	78/129
35	114/217	116/134	93/136	82/142
45	116/217	108/135	95/138	86/160
55	114/231	108/149	95/138	86/149
65	106/216	103/152	93/140	84/161

NOTES
*Blended braking (value on left-hand side)
**Friction-only braking (value on right-hand side)
AW0 weight.

TABLE 9-2. BRAKE SHOE WEIGHT LOSS.

Type of Shoe	Total loss of material for 16 blocks (lbs)	
	New	Half-Worn
WABCO 539	-0.93	-0.54
Abex T-176-4	-1.30	-0.92
Griffin Anchor	-0.82	-1.23

- In some cases, there was a rapidly rising retardation characteristic as the vehicle slowed in the friction-only braking mode.
- Noise levels were greatest during the last few seconds of braking.
- Vehicle weight and worn/half-worn shoes had little effect on noise or performance.
- The friction-only brake mode produced higher brake block temperatures, which in general produced lower noise levels.
- In general, of the three shoes tested, Abex T-276-4 produced the lowest noise levels, followed by Griffin Anchor, and then by WABCO 539.
- Wear rates among the shoes tested were similar, but the test was not long enough to establish values with confidence.

9.2 ENERGY CONSERVATION TEST PROGRAM

9.2.1 Test Objective

To evaluate potential reductions in energy consumption by modifying the vehicle speed/time curve, and to determine the tradeoffs in energy conservation vs. schedule time for operations on the MBTA Blue Line route.

9.2.2 Test Method

Four propulsion system parameters were modified to reshape the vehicles' speed/time characteristics:

- Acceleration level,
- Deceleration level,
- Cutoff speed (maximum speed at which propulsion power is removed by the vehicle control system), and
- Reset speed (speed to which the vehicle velocity falls from cutoff before power is automatically reapplied).

Figure 9-20 is a sample speed/time curve. The difference between the maximum allowable speed and the speed at which power was reapplied is defined as "bandwidth." The car overspeed circuit was used to control both the maximum speed attained and the reset speed of the propulsion system. It was possible to keep the master controller continuously in the power position while the overspeed circuit removed and reapplied power until the brakes were applied for a simulated station stop. Thus, for a series of tests, only two master controller positions were used, maximum power (P4) and full service brake. The setting of the overspeed circuit for both cutout and reset speed was verified by trial runs before each test series.

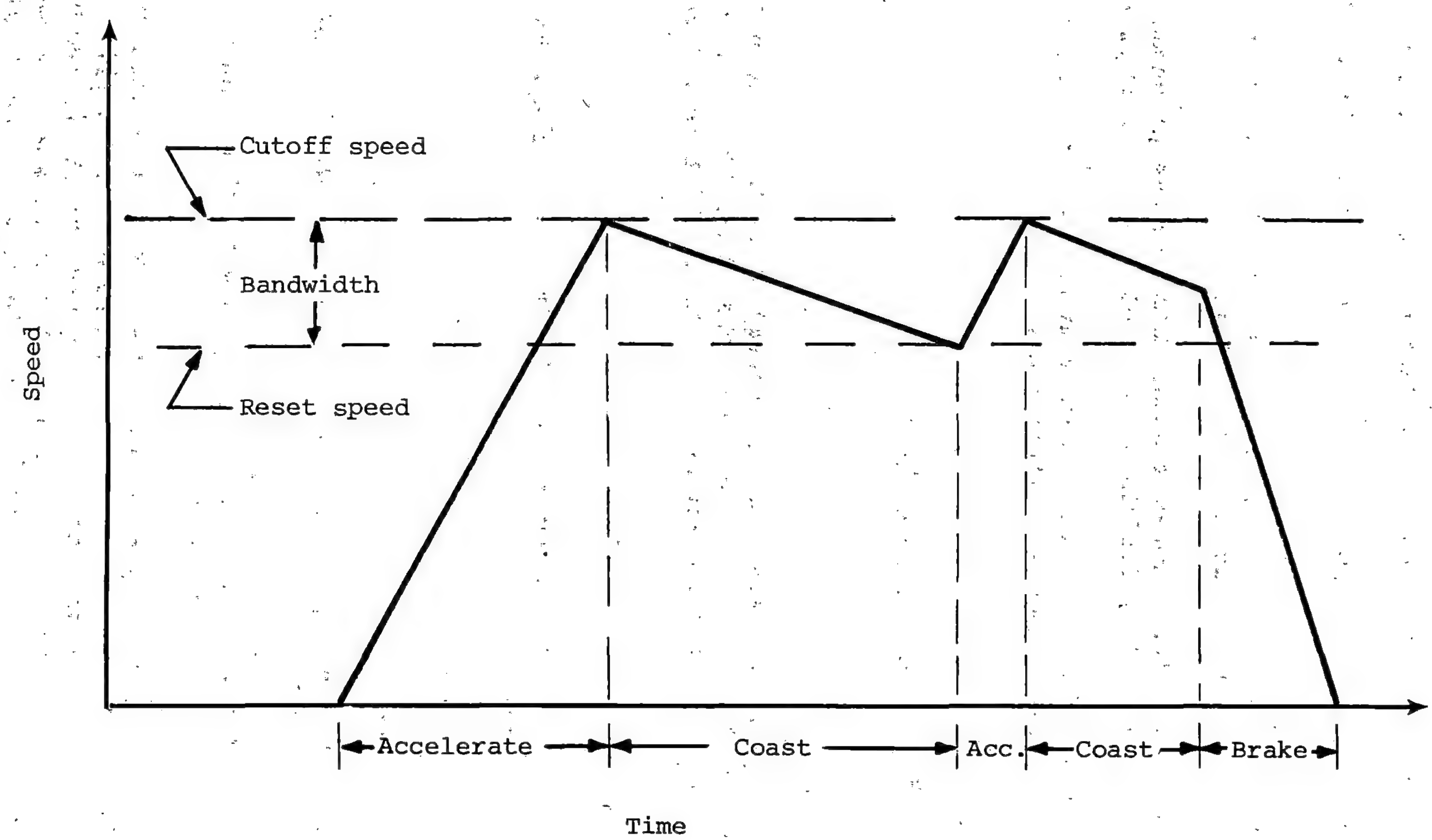


FIGURE 9-20. SAMPLE SPEED/TIME CURVE.

The approach to the energy conservation test phase was to attempt to reduce vehicle energy needs at high speed by reducing both the cutoff and reset speeds slightly. The resulting increase in schedule time between stations was then compensated for by increasing the acceleration and/or deceleration levels. The rationale was that train resistance becomes an ever-increasing function of speed squared as speed increases, due to the influence of aerodynamic drag. Therefore, trading high speed operation for an increase in acceleration or deceleration levels should result in an improvement in energy consumption, with minimal impact on schedule time.

The data runs were made over the simulated 10.26-mi MBTA Blue Line profile (5.13 miles each way), which had 22 station stops of 30 seconds each, with the exception of Wonderland, the turnaround station, where a 2-minute stop was made. Each profile run was repeated four times to establish the repeatability of the data.

9.2.3 Test Results

Table 9-3 shows the energy consumption and schedule performance for the configurations tested. The first configuration is the standard with an acceleration level of 2.5 mi/h/s and a deceleration level of 2.75 mi/h/s. All other configurations have both acceleration and deceleration levels of 3.0 mi/h/s. The configurations can be grouped together into two groups: configurations 2, 3, and 4 in which the cutoff speed was varied, and configurations 5, 6, and 7 in which reset speed was varied.

It can be seen from the table that lowering cutoff speed made a significant reduction of energy consumed, but that the lowering of reset speed was less effective.

All of the modifications to the vehicle control characteristics tested gave improved energy consumption; with the exception of configuration 2 (a 9% gain in energy consumed), all configurations tested required marginally increased time to complete the round trip.

Lowering the cutoff speed reduced the energy consumed by amounts varying from 9% to 22%, the greatest savings being for the lowest cutoff speed of 31 mi/h. This configuration however, required 2 minutes 01 seconds longer to complete a round trip than the standard configuration. Reducing the reset speed while holding the cutoff speed constant at 37 mi/h resulted in reducing the energy consumed by up to 11% with round trip time changes up to 29 seconds longer than standard.

The test program was successful in that energy saving configurations were identified. Their implementation in service will depend on the consideration of other factors, such as the impact of increased round trip time on passenger-carrying ability.

TABLE 9-3. ENERGY CONSERVATION FOR VARIOUS PROPULSION CONFIGURATIONS.

Configuration	Accel Level (mi/h/s)	Decel Level (mi/h/s)	Cutoff Speed (mi/h)	Reset Speed (mi/h)	Reset Bandwidth (mi/h)	*Traction Energy Consumed (kWh)	Change from Standard (%)	Time to Complete Round Trip (min-s)	Change Standard Time (%)
Standard - 1	2.5	2.75	40	38.1	1.9	115	---	33 - 34	---
Cutoff Speed Varied - 2	3.0	3.0	37	33.1	3.9	105	- 9	33 - 23	- 0.5
Cutoff Speed Varied - 3	3.0	3.0	34	30.0	4.0	96	-16	34 - 35	+ 3.0
Cutoff Speed Varied - 4	3.0	3.0	31	27.0	4.0	89	-22	35 - 35	+ 5.7
Reset Speed Varied - 5	3.0	3.0	37	28.9	8.1	102	-11	33 - 56	+ 1.1
Reset Speed Varied - 6	3.0	3.0	37	25.1	11.9	102	-11	34 - 03	+ 1.4
Reset Speed Varied - 7	3.0	3.0	37	33.0	4.0	105	- 9	34 - 02	+ 1.4

NOTES:

All runs made at AW3 weight.

Values are averaged from four repeated runs.

Traction energy consumed does not include operation of vehicle auxiliaries.

*Traction energy consumed as indicated by onboard wattmeters.

9.3 COUPLER MEASUREMENTS

Measurements were taken during the test program to identify the source of noise emanating under braking from the general area of the couplers between the married car pair. Displacement transducers were mounted between the ends of cars 0608 and 0609 and between the major components of each draft gear to measure the amount of run-in under braking and the clearance between components. The transducer locations are identified in appendix A, figure A-1. The outputs of the transducers were displayed on strip charts. In addition, closed circuit television cameras were mounted on the cars to observe the motion of the couplers.

The test data identified a series of cumulative machining tolerances which led collectively to excessive clearance in the draft gear assemblies, resulting in coupler noise under run-in and runout conditions. The draft gear clearances are currently being reviewed by MBTA and the vendor, and may result in a decision to modify the design to eliminate the problem.

10.0 CONCLUDING REMARKS

The following paragraphs summarize the quantitative aspects of test results derived from the Blue Line vehicle test program. The conclusions require qualification, in that they should be interpreted within the scope of this test program and the conditions at the TTC.

As an example, the acceleration levels experienced in the carbody during the ride quality phase of the program are a product of the transfer functions of the trucks, suspension, carbody, and the input from the track; given that the transfer functions remain constant, the accelerations experienced are a function of the quality of the TTT. The only conclusion that can be made from the ride quality tests, therefore, is that ride quality defined in the report is representative of ride on track maintained to FRA Class 6 standards, with a maximum curvature of $1^{o}50'$.

The Blue Line vehicles met most design specification requirements; the specification defines criteria for acceleration and braking performance, wayside and interior noise levels, and component induced vibration.

In the area of performance criteria, the vehicles were marginally below the requirement for maximum average acceleration (by 0.1 mi/h/s) but were able to meet time-to-speed criteria; acceleration variation and jerk rates were acceptable. The cars showed good control linearity and compensation for passenger load for both acceleration and deceleration. In the braking mode, the cars met the specification requirement for a full service braking rate of 2.75 mi/h/s for blended braking under EP control. They were able to demonstrate that the full service rate was available from friction-only braking in the event of failure of the dynamic braking system.

Braking controlled by SAP pressure, a fail-safe backup mode to the normal EP mode, gave slightly lower deceleration levels than the specification requirement (0.25 mi/h/s lower). As for acceleration, braking showed good linearity of response and compensation for passenger load. Dynamic-only braking was effective down to 15 mi/h at the lowest weights, and to 15-18 mi/h at rush hour passenger load; the specification requirement is 15 mi/h. The vehicles met the acceleration variation and jerk limit requirements in the blended braking mode, but not for friction-only braking. Emergency braking requirements were met at the lower vehicle weights, but not for the rush hour passenger load case, where the deceleration was as much as 0.45 mi/h/s below the specification requirement, depending on the mode of initiation.

Friction braking duty cycle and energy consumption tests were carried out using simulated revenue runs representing the MBTA Blue Line and several other revenue profiles from other transit properties. During friction brake duty cycle runs, the brake shoe temperatures stabilized at 200-210^{o}F. Brake temperatures in service are likely to be higher due to local conditions such as operation in tunnels with limited air circulation. Energy consumption for the two-car train operating over a simulation of the MBTA Blue Line varied between 11.82 and 12.20 kWh/mi.

The vehicles met the wayside interior noise level criterion of 70 dBA; levels were generally in the 68-72 dBA range with transients to 72-74 dBA due

to switches and grade crossings. There was no criterion for interior noise for the vehicles in motion.

Wayside noise levels, during the vehicles' passing by a wayside location 50 ft from the track centerline, exceeded the criterion of 80 dBA at 50 ft at speeds in excess of 40 mi/h. Noise levels peaked at 87-90 dBA at 60 mi/h. The vehicles can be considered satisfactory and within specification for operation on the Blue Line at speeds up to 40 mi/h.

The vehicle met the only specification requirement for ride quality, that instantaneous acceleration due to component induced vibration should not exceed 0.04 g.

The basic reliability of these cars was above average. Not one scheduled test day was cancelled because of vehicle failure even though the married pair of cars accumulated 11, 263 mi of running on the TTT. The accessibility of car components, ease of inspection, maintenance, and repairs made a great contribution to the success of the MBTA Test Program.

The cars were operated for a total of 743 hours out of 752 hours scheduled for operation, for a utilization of 99% (running hour/scheduled hour), an indicator of the high degree of reliability of the cars.

As a result of special engineering tests conducted at the request of MBTA, three types of experimental brake shoes were evaluated. They were found to have performance equal to the standard equipment brake shoes up to 40 mi/h, but, with the exception of the Griffin Anchor shoe, to be inferior with respect to stopping distance above this speed.

Several propulsion control configurations were identified that could result in energy savings for operation of the vehicles over the Blue Line. Their adoption will depend on the acceptance of higher acceleration/braking rates, lower top speeds, and possible increases in round trip times. For example, higher braking times may result in higher brake wear rates which could, in part, negate the energy consumption gains.

REFERENCES

1. Guide for the Evaluation of Human Exposure to Whole-Body Vibration, ISO.2631-1978 (E) TC-108.

2. Track Safety Standards, FRA Office of Safety, March 1975.

References

APPENDIX A

INSTRUMENTATION, DATA ACQUISITION, AND DATA PROCESSING

This appendix describes the systems used to acquire test data for the MBTA Blue Line Test Program.

1.0 INSTRUMENTATION

1.1 INTRODUCTION

Instrumentation requirements for the MBTA test program were divided into four basic groups according to the type of test to be performed:

- Performance (acceleration, deceleration, power consumption),
- Vehicle dynamics (ride quality),
- Noise (community, passenger), and
- Special engineering (energy consumption, brake shoe-induced noise, truck dynamics, and coupler noise).

1.2 PERFORMANCE AND VEHICLE DYNAMICS

Performance, vehicle dynamics, and certain special engineering test phases were conducted using a series of sensors mounted on the cars. The measurement number, standard output, and sensor description for each particular test set are shown in tables A-1 and A-2. Current and brake cylinder pressure sensors were divided to obtain data from each car of the married pair, and where appropriate, for each truck of each car. Longitudinal acceleration was measured by a Servo accelerometer mounted on the floor of one of the cars. Speed information was recorded from a standard car sensor and was also processed through a speed/distance chassis, described in section 3-1, to produce a pulse output, each pulse representing 10 ft. A sensor located on the front truck was used to detect steel targets mounted on the track crossties at 1,000-ft intervals that were recorded as a pulse on one data channel; a voice track and a remotely operated event marker were also used to annotate the data recordings. The sensor listing was derived from the recommended "Standard Outputs" for performance testing, detailed in the General Vehicle Test Procedure (GVTP)[1]. The types of transducer and their required accuracies match the requirements of GVTP.

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[1] General Vehicle Test Plan (GVTP) for Urban Rail Transit Cars, Report No. UMTA-MA-06-0025-75-14.

TABLE A-1. INSTRUMENTATION SENSOR LISTING, PERFORMANCE.

CHANNEL NUMBER	PARAMETER	STANDARD OUTPUT NAME	MEASUREMENT NUMBER	SENSOR TYPE	MEASUREMENT RANGE	MAXIMUM CUTOFF FREQUENCY
1	IRIG-B Time	T/A	01411	Time Code Generator	---	1 KHz
2	Line Voltage	LVD/A	01101	Resistive Divider	0-1000 V d.c.	200 Hz
3	Line Current, A Car	LCD/A	01102	Shunt	0-1500 A	200 Hz
4	Motor Current Front, A Car	MACD/AF	01103	Shunt	0-600 A	200 Hz
5	Motor Current Rear, A Car	MACD/AR	01104	Shunt	0-600 A	200 Hz
6	Load Weigh, A Car	LW/A	01204	Strain Gage	74-95 psi	50 Hz
7	Straight Air Pipe, A Car	SAP/A	01203	Strain Gage	0-100 psi	50 Hz
8	Brake Cylinder Press., A Car	BCP/A	01201	Strain Gage	0-50 psi	50 Hz
9	Line Current, B Car	LCD/A	01105	Shunt	0-1500 A	200 Hz
10	Motor Current Front, B Car	MACD/AF	01106	Shunt	0-600 A	200 Hz
11	Motor Current Rear, B Car	MACD/AR	01107	Shunt	0-600 A	200 Hz
12	Load Weigh, B Car	LW/A	01208	Strain Gage	74-95 psi	50 Hz
13	Straight Air Pipe, B Car	SAP/A	01207	Strain Gage	0-100 psi	50 Hz
14	Brake Cylinder Press, B Car	BCP/A	01205	Strain Gage	0-50 psi	50 Hz
15	Brake Temp. Rotational	BT/A	03201	Thermocouple*	0-1000 °F	1 Hz
16	Brake Temp. Stationary	BT/B	03202	Thermocouple*	0-1000 °F	1 Hz
17	Controller Setting	CS/A	01301	Composite Signal	---	10 Hz
18	Distance	D/A	01421	Pulse Generator	10 ft/pulse	1 KHz
19	ALD	ET/A	01422	Displacement Sensor	---	50 Hz
20	Event	ET/A	01423	Switch	---	---
21	Speed	VS/A	01401	Proximity Sensor	80 mi/h	10 Hz
22	Vehicle Accel/Decel.	AP/A	02001	Servo Accel	± 5 mi/h ps	3.15 Hz
23	Brake Pipe Pressure	BPP/A	01206	Train Line Signal**	0-100 psi	---
27	Tape Speed Reference					
28	Voice					

* TYPE "E" THERMOCOUPLES (CHROMEL-CONSTANTAN)

** TRAIN LINE SIGNAL ON = 110 psi
OFF = 0 psi

TABLE A-2. INSTRUMENTATION SENSOR LISTING, RIDE QUALITY.

CHANNEL NUMBER	PARAMETER	STANDARD OUTPUT NAME	MEASUREMENT NUMBER	SENSOR TYPE	MEASUREMENT RANGE	MAXIMUM CUTOFF FREQUENCY
1	IRIG-B Time	T/A	01411	Time Code Generator	---	1 KHz
2	Accel. Fwd. Car Floor CL Vert.	AC/A1	02101	Servo Accel.	± 5 g	100 Hz
3	Accel. Fwd. Car Floor CL Lat.	AC/A2	02102	Servo Accel.	± 0.5 g	100 Hz
4	Accel. Fwd. Car Floor CL Long.	AC/A3	02103	Servo Accel.	± 0.5 g	100 Hz
5	Accel. Midcar Floor CL Vert.	AC/A4	02104	Servo Accel.	± 5 g	100 Hz
6	Accel. Midcar Floor CL Lat.	AC/A5	02105	Servo Accel.	± 0.5 g	100 Hz
7	Accel. Midcar Floor Left Vert.	AC/A6	02106	Servo Accel.	± 5 g	100 Hz
8	Lead Axle Right Journal Vert.	AJ/A1	02201	Piezo Accel.	± 30 g	1 KHz
9	Lead Axle Right Journal Lat.	AJ/A2	02202	Piezo Accel.	± 10 g	1 KHz
10	Lead Axle Left Journal Vert.	AJ/A3	02203	Piezo Accel.	± 30 g	1 KHz
11	Side Frame Front Left Vert.	SFFLV	02204	Capacitance Accel.	± 5 g	300 Hz
12	Traction Motor Vert.	TMV	02209	Piezo Accel.	± 10 g	300 Hz
13	Traction Motor Lat.	TML	02210	Piezo Accel.	± 10 g	300 Hz
14	Traction Motor Long.	TMLO	02211	Piezo Accel.	± 10 g	300 Hz
15	Side Frame Front Right Vert.	SFFRV	02205	Capacitance Accel.	± 5 g	300 Hz
16	Side Frame Front Right Lat.	SFFRL	02206	Capacitance Accel.	± 5 g	300 Hz
17	Side Frame Rear Right Vert.	SFRRV	02207	Capacitance Accel.	± 5 g	300 Hz
18	Side Frame Rear Right Lat.	SFRRL	02208	Capacitance Accel.	± 5 g	300 Hz
19	ALD	ET/A	01422	Displacement Sensor		50 Hz
20	Event	ET/A	01423	Switch	---	---
21	Speed	VS/A1	01401	Proximity Sensor	80 mi/h	10 Hz
22	Distance	D/A	01421	Pulse Generator	10 ft/pulse	1 KHz
23	Controller Setting	CS/A	01301	Composite Signal	---	10 Hz
27	Tape Speed Reference					
28	Voice					

Ride quality sensors were mounted on one truck and in one carbody. The carbody sensors were positioned at the forward end over the truck and at a midcar location to sense vertical, lateral, and longitudinal accelerations. The locations of the vehicle body accelerometers are shown in figure 8-1 and the truck-mounted accelerometers in figure 8-2. The truck accelerometers were positioned to sense accelerations of the lead axle, the truck side frame, and the motor.

1.3 NOISE TESTS

Noise tests were conducted using two portable sound level meters to survey the test areas. These sound level meters were set to dB scale, A-weighted and slow response. Microphone locations for each test set are shown in figure 7-3.

1.4 SPECIAL ENGINEERING TESTS

1.4.1 Energy Conservation Test Program

Instrumentation sensors for the energy consumption tests were the same as for performance data (table A-1), with the exception of electrical current measurements. Total line current measurements (no's. 01102 and 01105) were discontinued and the sum of the two propulsion currents for each car was used instead. This allowed energy consumption to be calculated for only the propulsion systems, excluding power consumed by the vehicle auxiliaries. Additional temperature measurements, listed below, were also taken:

Thermocouple Location	Vehicle
Ambient, outside midcar	0609
Ambient, near leading motor	0609
Traction motor, top leading motor	0609
Traction motor, bottom leading motor	0609
Ambient, near leading motor	0608
Traction motor, top leading motor	0608
Traction motor, bottom leading motor	0608
Metal surface under resistor bank	0609
Near cable insulation on resistor bank	0609
Top of resistor bank	0609

1.4.2 Brake Shoe Test

Data channels for the brake shoe-induced noise testing remained the same as for performance testing (table A-1). In addition, two sound level meters were used to monitor noise levels. Microphone locations were:

- External, right front door at approximately ear level for a station bystander, and
- Internal, front of car opposite motorman's cab, at a seated passenger's ear level.

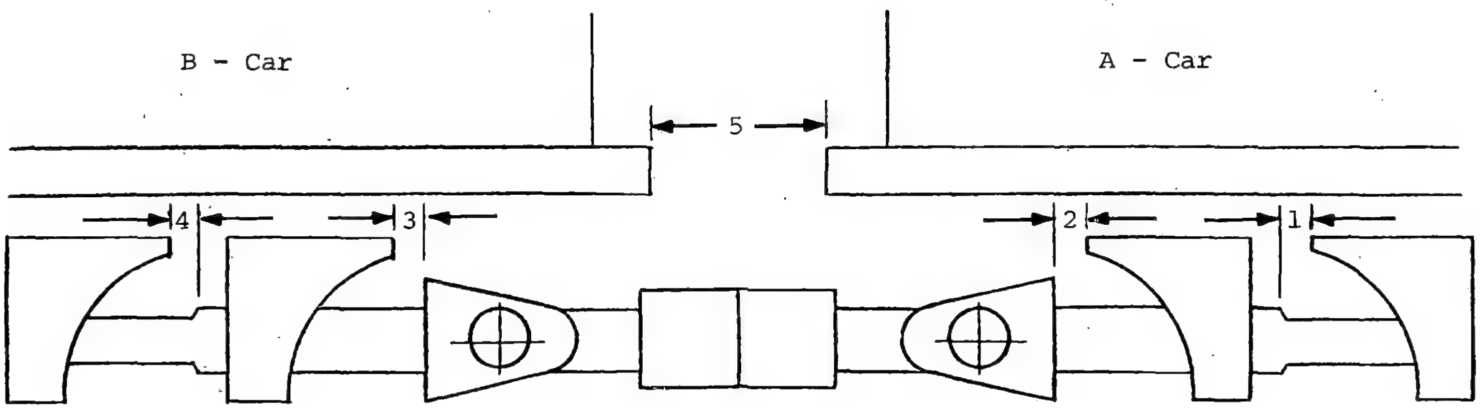
The meters were set to an A-weighted dB scale with slow response. The d.c. output of these meters was also recorded on a multichannel strip chart.

The following additional brake temperature measurements were also provided:

Thermocouple Location	Vehicle
Ambient, outside	0609
Ambient, second wheel left side	0609
Surface of brake shoe, second wheel left side	0609
Ambient, second wheel right side	0608
Embedded, second wheel right side	0608
Surface of brake shoe, second wheel right side	0608

1.4.3 Coupler Noise

Coupler noise tests required the installation of displacement transducers at various locations on the coupler assembly. Figure A-1 shows the five designated locations. Coupler displacements were recorded on strip charts only. The coupler measurements were taken during actual running of the vehicles, with the vehicles stationary, and with a rocking motion applied to the cars.



Locations:

1 & 4 - Draw bar pin measurement

2 & 3 - Yoke pin measurement

5 - Train to train measurement

FIGURE A-1. DISPLACEMENT TRANSDUCER LOCATIONS, COUPLER ASSEMBLY.

2.0 DATA ACQUISITION

The onboard analog data acquisition system consisted of signal conditioning, filters, strip chart recorders, and one 28-track tape recorder. A schematic of the basic system is shown in figure A-2. The data acquisition system, as implemented onboard the MBTA vehicle, is shown in figures A-3 and A-4.

2.1 SIGNAL CONDITIONING AND MONITORING ELECTRONICS

The signal conditioning system, an ENDEVCO 4470 unit, provided excitation voltages for transducers, sensors, and for preconditioning circuits. The 4470 also provided amplification as required to normalize all analog signals to a ± 5 V level. The SM-1 signal monitor provides real-time static monitoring (digital multimeter) and dynamic monitoring (oscilloscope) of any analog data signals. The signal conditioning system is described below, and the signal monitoring system is described in detail in a standard instrumentation manual.[2]

The ENDEVCO 4470 has 35 separate channels, each of which is composed of a modular unit and a plug-in "mode" card. Seven rack adapters provide for mounting of the modules in a standard 19" rack, five modules per adapter, and provide interconnections for power, signal input, signal output, and monitor and calibration functions. The modular unit is a package containing circuit components common to most conditioning circuits. It contains a regulated instrument power supply, calibration circuits, and interconnections for each plug-in mode card.

The mode card contains circuit components designed for a specific type of signal conditioning. Conditioning functions of the measurement system are all routed through the mode card, and the function of a particular module is "specialized" by the card installed. Any module can be used to perform any conditioning function by installing the appropriate card. Cards may have a standard circuit configuration or a custom circuit. The block diagram and interconnection of the cards are shown in figure A-2.

2.2 SIGNAL FILTERING ELECTRONICS

An Ithaco type 4113 system was used to enhance the signal-to-noise ratio of the measurement systems and to minimize signal "aliasing" during digitization. The system is made up of 32 separate channels of low-pass filter networks. Each channel is switch-selectable between 4-pole Bessel (linear phase delay) or 4-pole Butterworth (maximum flat amplitude response) filter characteristics. The cutoff frequency of each channel can be varied from 1 Hz to 1 MHz. Each of the separate filters (Ithaco 4113M101) is an integral modular unit. Eight of these modules were installed in a rack-

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[2] General Vehicle Test Instrumentation Manual, Report No. UMTA-MA-06-0025-77-17.

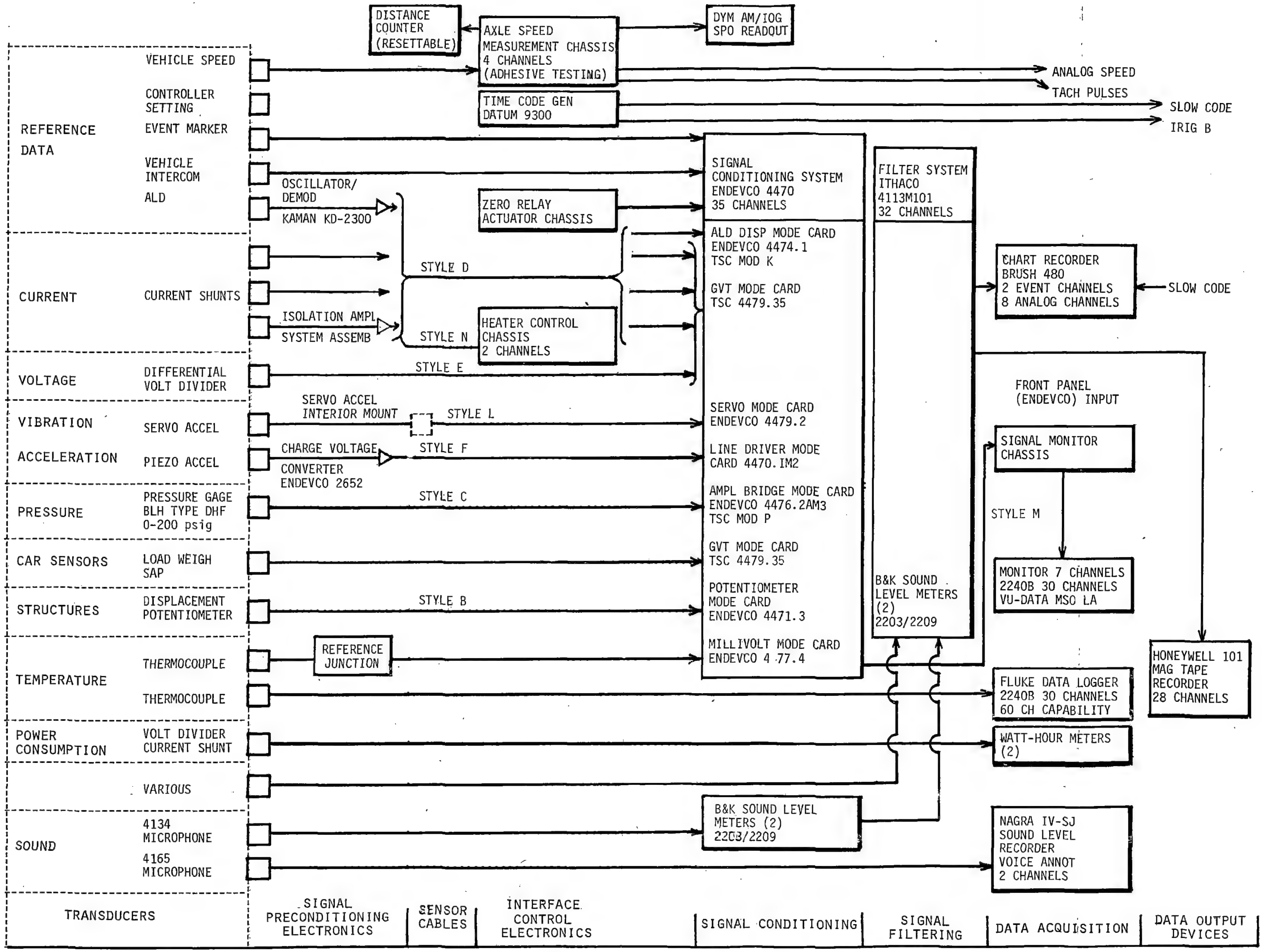

FIGURE A-2. BLOCK DIAGRAM, DATA ACQUISITION SYSTEM.

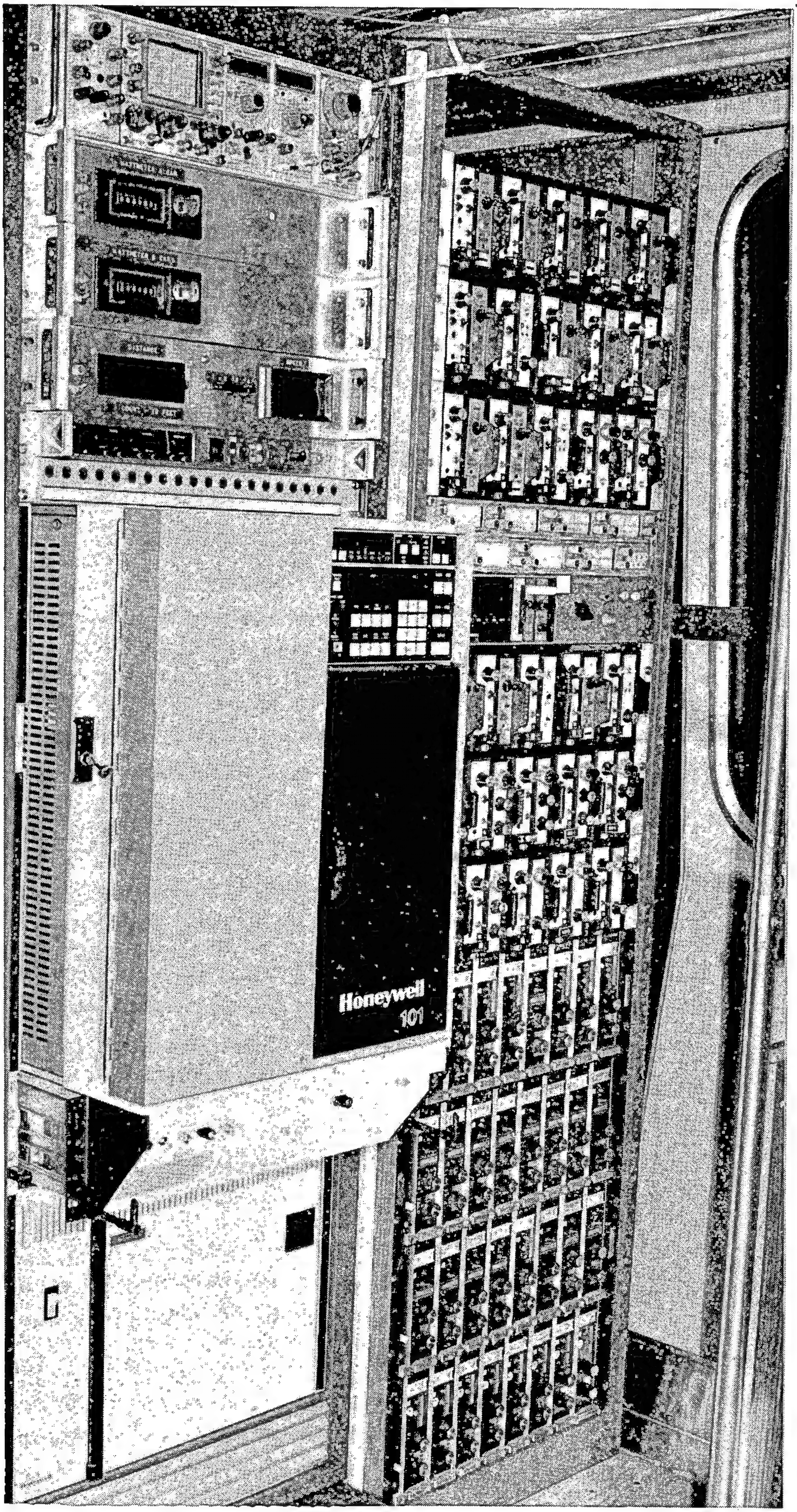

FIGURE A-3. DATA ACQUISITION SYSTEM, VIEW 1.

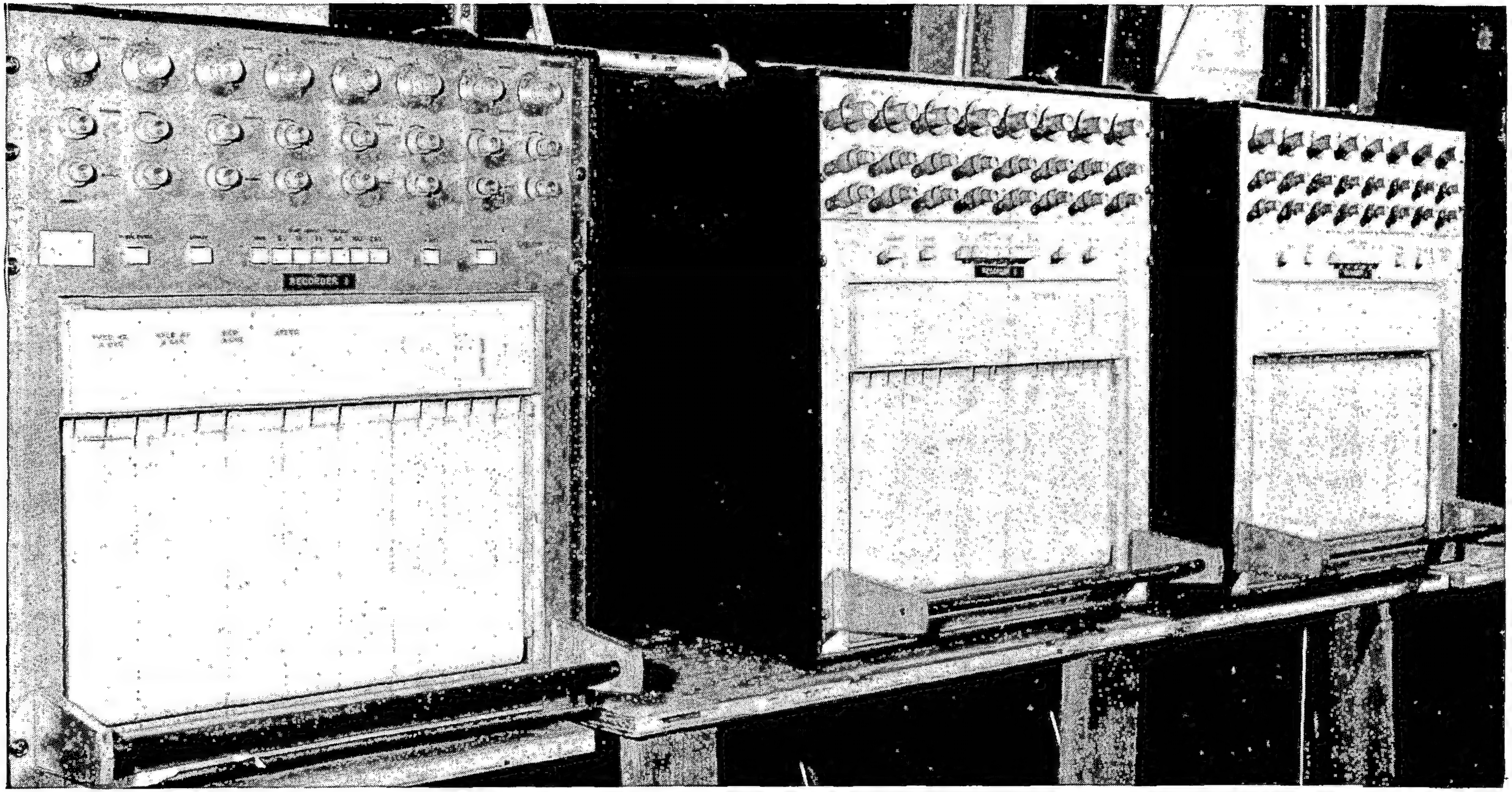

FIGURE A-4. DATA ACQUISITION SYSTEM, VIEW 2.

mounted adapter which provided a common a.c. power input, switch, indicator lamp, and fuse.

2.3 STRIP CHART RECORDERS

The strip chart recorders that were used to monitor test progress online consisted of three Brush model 480 8-channel recorders.

2.4 TAPE RECORDER

The analog tape recorder used was a Honeywell model 101 portable magnetic tape recorder/reproducer with microcomputer control. The tape heads were 28 track, IRIG configuration.

The tape recorder setup for MBTA testing is listed in table A-3.

TABLE A-3. TAPE RECORDER CONFIGURATION.

Track	Record/Reproduce	Data
#1	Direct	IRIG-B time code
#2-#26	FM	Data channels
#27	FM Shorted input to record center frequency as a reference signal	
#28	Voice	Voice

The FM data channels were set to 5 V d.c. = 40% deviation, at a tape speed of 1-7/8 in/s. The center frequency was 3.375 kHz with +40% = 4.725 kHz and -40% = 2.025 kHz.

3.0 TTC-FABRICATED SPECIAL PURPOSE EQUIPMENT

3.1 SPEED AND DISTANCE CHASSIS

The speed and distance chassis used four differential tachometer inputs to provide discrete analog speed outputs for each axle. In addition, the unit provided a pulse output proportional to distance travelled. Each tachometer pulse was fed to a programmable divider of 1, 2, 5, or 10, which provided a frequency proportional to speed to a frequency-to-voltage converter. This in turn gave an analog voltage output proportional to actual speed. The analog voltage was then displayed on a digital voltmeter. The distance circuit divided the pulse rate by a series of programmable dividers (units, tens, and hundreds) to provide 1 pulse-per-ft, 1 pulse-per-10 ft, etc. This desired pulse rate was then presented on a 6-digit counter display.

The chassis was designed and constructed at the TTC, and a circuit diagram of the speed and distance chassis is kept on file.[3]

3.2 ENERGY CONSUMPTION WATT-HOUR METER

Energy consumption data were acquired during the test program by means of a watt-hour meter chassis, designed and constructed at the TTC. The chassis used an analog multiplier to provide an output, from scaled voltage inputs of voltage and current sensors, proportional to instantaneous power consumption. The output of the multiplier was then integrated with respect to time by an integrating voltage-frequency converter. This device produced a pulse frequency proportional to applied voltage. Each pulse represented an increment of energy, the sum of which represented total energy. Output from the frequency converter was then conditioned in a divider/counter driver circuit, using three scalable counters and a monostable multivibrator. This driver circuit acted as a pulse stretcher to increase the pulse width to the 20-ms minimum required to drive a 6-digit mechanical counter (one for each car of a married pair), which totalled power consumption over the duration of a test run.

A functional description of the system[4] and a circuit diagram of the watt/hour meter chassis[5] are maintained by the TTC.

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[3] "Drawing Number I-3047-79," Transportation Test Center, December 11, 1979.

[4] "Functional Description of Watt-Hour Meter," TTC Memo IE/DG/76-109, November 23, 1976.

[5] "Drawing Number SK-RDL-4255," Transportation Test Center, January 4, 1977.

4.0 DATA PROCESSING

The following paragraphs describe the methods used to select data slices of interest for post-test data processing, and the processing, smoothing, and data presentation techniques used for data in this report.

4.1 DATA SELECTION

Up to 28 channels of analog data were recorded FM on magnetic tape onboard the test vehicle. Selected data were simultaneously recorded on three strip chart recorders, also on the vehicle; these were used to assure the quality of the data, to monitor the progress of the test, and to allow engineering judgements to be made with regard to the course of the test. At least once during the test day, the data recorded on magnetic tape and the calibration levels for each channel were played back through the strip chart recorders to ensure that the signal amplitudes were as expected.

Time slices of data to be analyzed were selected by reviewing the strip chart for a particular test and noting the start and stop times of the data of interest, using the IRIG "slow" binary time code (IRIG-B) on the chart. The analog tapes were then forwarded to TTC Computer Center for digitizing, together with tape logs detailing the start and stop times and the data channels of interest. A chart illustrating the data processing flow is shown in figure A-5.

4.2 PERFORMANCE DATA

Performance data were digitized on a Varian V-76 computer at 32 samples per second; digitized data were converted to engineering units and listed or recorded on punched cards every eighth sample (i.e., every ¼ second of the test run). When further smoothing of the data proved necessary, a moving average technique was adapted. The punched cards were entered into an HP 9845 desktop computer that smoothed the data over 12 consecutive data points (i.e., 3 seconds of test data). This moving average took data inputs 1 through 12, averaged them and presented them as smoothed data for the sixth-time input. It then performed a similar average for samples 2 through 13, 3 through 14 ...1+n through 12+n, up to 12+n samples.

The performance data were plotted using the HP 9845, integrated with an X-Y plotter. Crossplots were also made from the V-76 engineering listing by entering them on a graphics terminal to the X-Y plotter.

4.3 RIDE QUALITY DATA

Ride quality data were digitized at 200 samples per second, and then processed using Fast Fourier Transform algorithms to produce PSD and rms values.

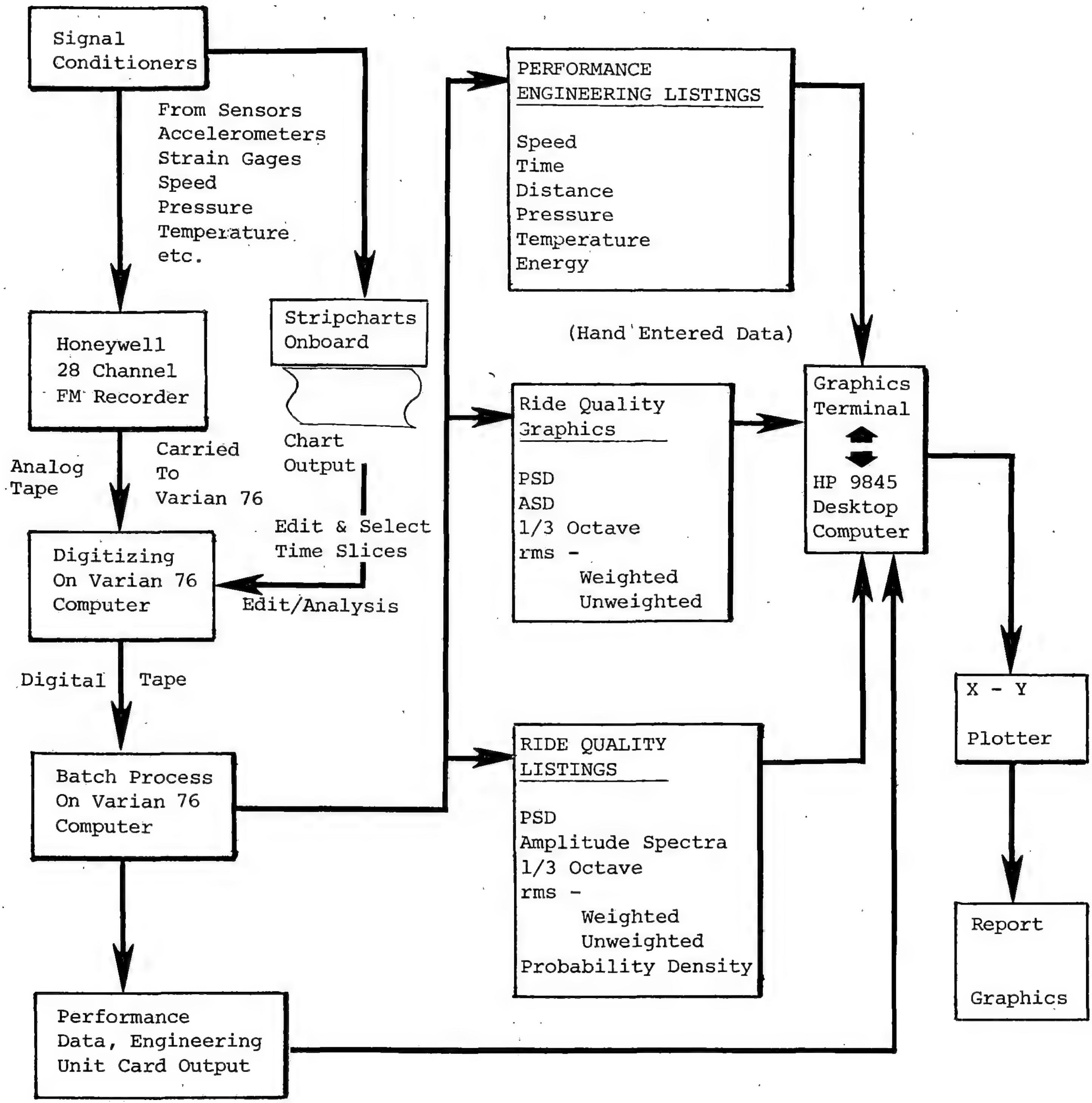

FIGURE A-5. DATA PROCESSING FLOW CHART.

The rms values were weighted for human whole-body response[6] to vibration, and unweighted for more generalized analysis. Listings and machine plots were produced.

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[6] Guide for the Evaluation of Human Exposure to Whole-Body Vibration, ISO 2631-1978 (E) TC-108.

5.0 DATA MANAGEMENT AND DOCUMENTATION

Over 900 test runs were made to achieve the objectives of the test program for the MBTA rapid transit cars. An important factor, therefore, in the presentation of MBTA data is adequate documentation of the test run log and data logging procedures to give a potential user easy access to the raw data in his field of interest.

This section describes the methods used to document test runs, weather conditions, vehicle weight, and other significant test factors, and to document sensor sensitivities, channel assignments, and analog tape data content.

5.1 DAILY TEST RUN LOGS

Test run log sheets were completed for each test objective throughout the test program. These sheets identified the test program, the GVTP test set numbers, date of test, vehicle consist and weight, and all other test variables, together with any other notes pertinent to the test. Each test run was identified by a consecutive run number. Direction of travel, controller position, speed, track station number (where relevant), and time of day were logged for each run. The test run log sheets are kept on file at the TTC.

A test and run number cross reference was prepared from the daily log sheets. It is included as appendix C, and allows the data user to correlate the test program objective of interest with run numbers identifying tests to meet those objectives, and with the reference numbers of the raw data magnetic tape.

5.2 DATA ACQUISITION LOG SHEET AND TAPE LOG

The prime purpose of the data acquisition and tape logs was to maintain an accurate record of the content of the analog raw data tapes. The data acquisition log gives a precise account of the instrumentation sensors in use for any given test series and their channel assignments on the data tape. Detailed for each channel are the measurement name, type of transducer sensitivity, system sensitivity, filtering applied, tape calibration, equivalent engineering values, etc. The log was updated during the test program for each instrumentation change and a notation was made to indicate the test runs for which that log sheet was valid. A copy of the data acquisition log sheet was made for each day's testing and was attached to the tape log for that day.

The tape log gives an account of the content of each raw data tape in terms of the test run numbers on the tape and their location. During the test program, a log was maintained of each test run number, the start and stop of the test run in tape footage, and the start and stop times from the time code generator display on the data system console. A standard time code (IRIG-B) format was maintained on channel #1 of the tape recorder through the test program. Correlation of this time code with the noted time of day in the tape log (taken from the same time code generator display) gives the precise

location of each test run on the data tape for post-test data analysis. In addition to the time correlation on channel #1, channel #28 was used for voice annotation where the test set number, run number, track section, car speed, and any comments were noted for each run. These original tape and log sheets are stored at the TTC.

6.0 REFERENCES

1. General Vehicle Test Plan (GVTP) for Urban Rail Transit Cars, Report No. UMTA-MA-06-0025-75-14.

2. General Vehicle Test Instrumentation Manual, Report No. UMTA-MA-06-0025-77-17.

3. "Drawing Number I-3047-79," Transportation Test Center, December 11, 1979.

4. "Functional Description of Watt-Hour Meter," TTC Memo IE/DG/76-109 November 23, 1976.

5. "Drawing Number SK-RDL-4255," Transportation Test Center, January 4, 1977.

6. Guide for the Evaluation of Human Exposure to Whole-Body Vibration, ISO.2631-1978 (E) TC-108.

APPENDIX B

DRIFT TEST DATA ANALYSIS

This appendix contains information, observations, and comments on drift test data analysis techniques for transit vehicle testing that the authors believe to be of value for future planning.

Experimental results were compared with Davis formula predictions. The specification indicated that design calculations for train resistance should use the Davis formula:

$$R = 1.3 + \frac{29}{W} + bV + \frac{cAV^2}{WN},$$

where:

R = resistance in pounds per ton,

W = average weight in tons per axle of locomotive or car,

N = number of axles,

b = coefficient of flange friction effects,

V = velocity of train in mi/h,

c = aerodynamic drag coefficient (based on frontal area), and

A = frontal area in square feet.

The suggested factors from the vehicle specification for train resistance are:

b = 0.045 for all cars,

c = 0.0024 for the lead car and 0.00034 for the trailing cars, and

A = 100 ft^2.

This empirical formula, when used with the factors suggested in the specification, gives a result shown in figure B-1. Here two curves are shown for the Davis formula, one calculated for sea level and the other calculated for 4,900 ft (altitude of the drift test site) by the addition of a density

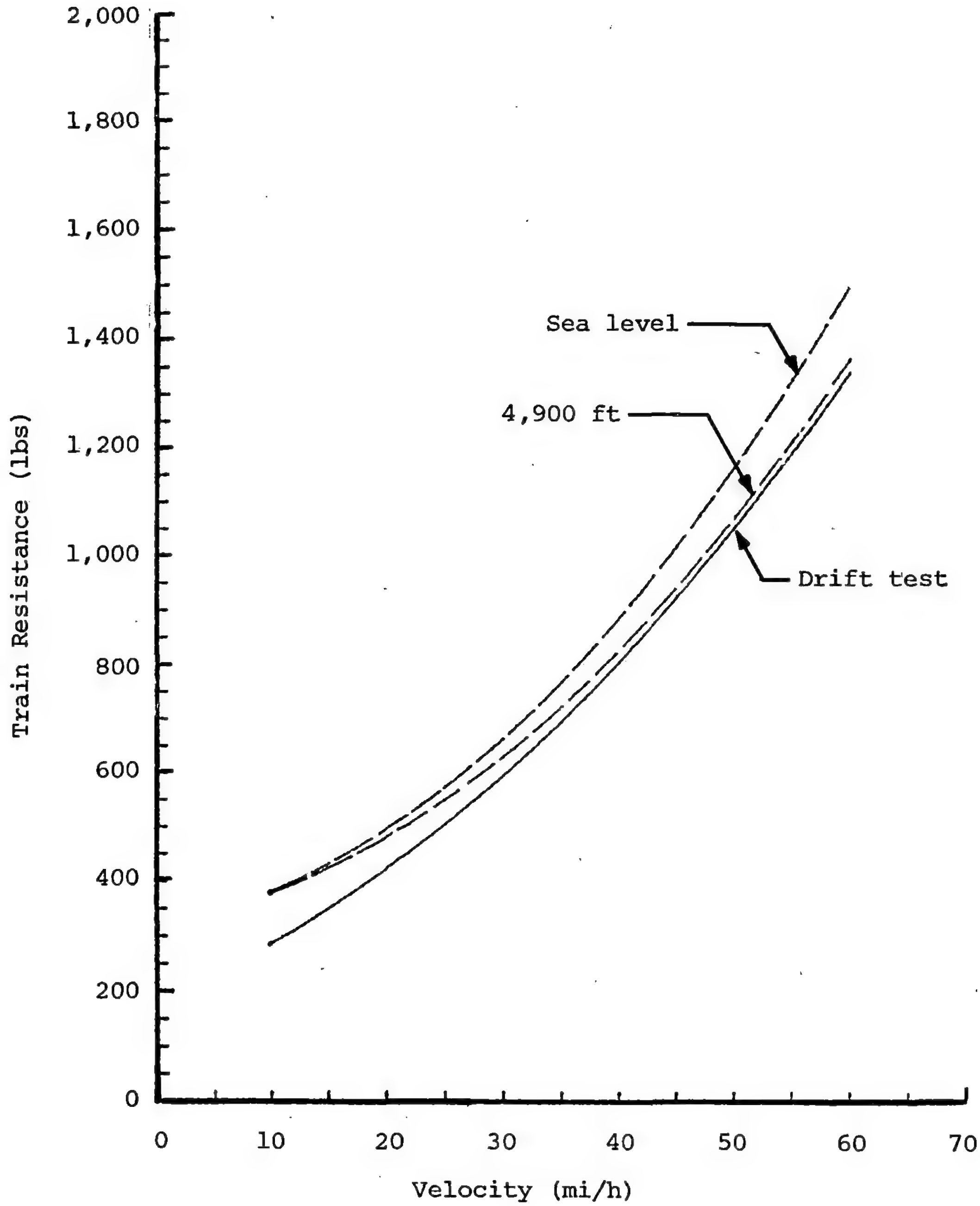

FIGURE B-1. COMPARISON OF VEHICLE SPECIFICATION DAVIS FORMULA CURVES AND DRIFT TEST DATA, AW2 WEIGHT.

correction factor of 0.864, to the last term only (the aerodynamic drag term). In this case, the Davis formula and the suggested coefficients give a fair approximation of the overall resistance obtained by the drift experiment. It should be noted that although the overall train resistance calculated by the Davis formula is a good approximation in this case, it does not validate the value of each term in the formula as calculated. It indicates only that this summation is approximately correct.

The polynomial curve fit to the experimental data produced coefficients for A_0, A_1, and A_2 of widely differing values, in one case, negative (table 6-8). This was caused by the large scatter in the data pairs of deceleration and velocity, which was in turn brought about by velocity transients in the original data. The contribution to train resistance that depends directly on velocity ("flange effects") is small; therefore, in the case of scattered data, it may be more practical to fit a curve of the form:

$$\text{Resistance} = A_0 + A_2V^2.$$

Some empirical train resistance formulas use this form of the expression.

The composite data, both CW and CCW, for AW0, AW1, and AW2 were fitted with the above curve form and produced the resistance coefficients listed in table B-1.

TABLE B-1. DECELERATION COEFFICIENTS.

Weight	Coefficient A_0	Coefficient A_2
AW0	0.0505	0.00047
AW1	0.0483	0.00039
AW2	0.0415	0.00045

The curves associated with these coefficients are shown in figure B-2. In figure B-3, the drift test at AW2 weight, fitted with these coefficients, is shown for comparison with the Davis formula calculated for AW2 weight.

The drift test provided useful train resistance data, but the analysis was not adequate to separate the differences in train resistance at the three weights tested. To avoid problems in analysis, future tests should cover the vehicle speed range from top speed to zero. Tests should be performed in very low (less than 3 mi/h) wind conditions because wind effect on the aerodynamic

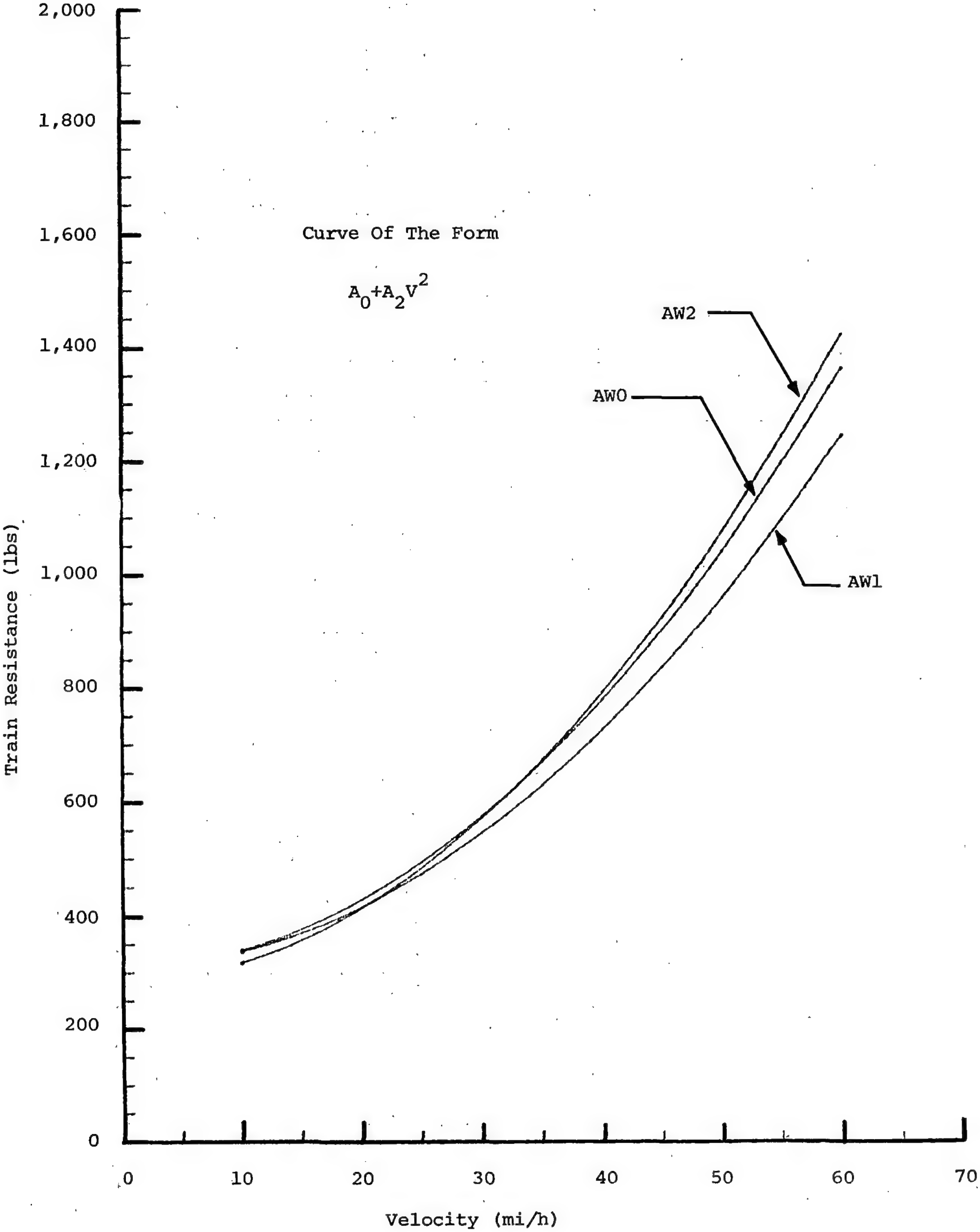

FIGURE B-2. TRAIN RESISTANCE DERIVED FROM AN $R=A_0+A_2V^2$ CURVE FIT OF TEST DATA FOR THREE VEHICLE WEIGHTS.

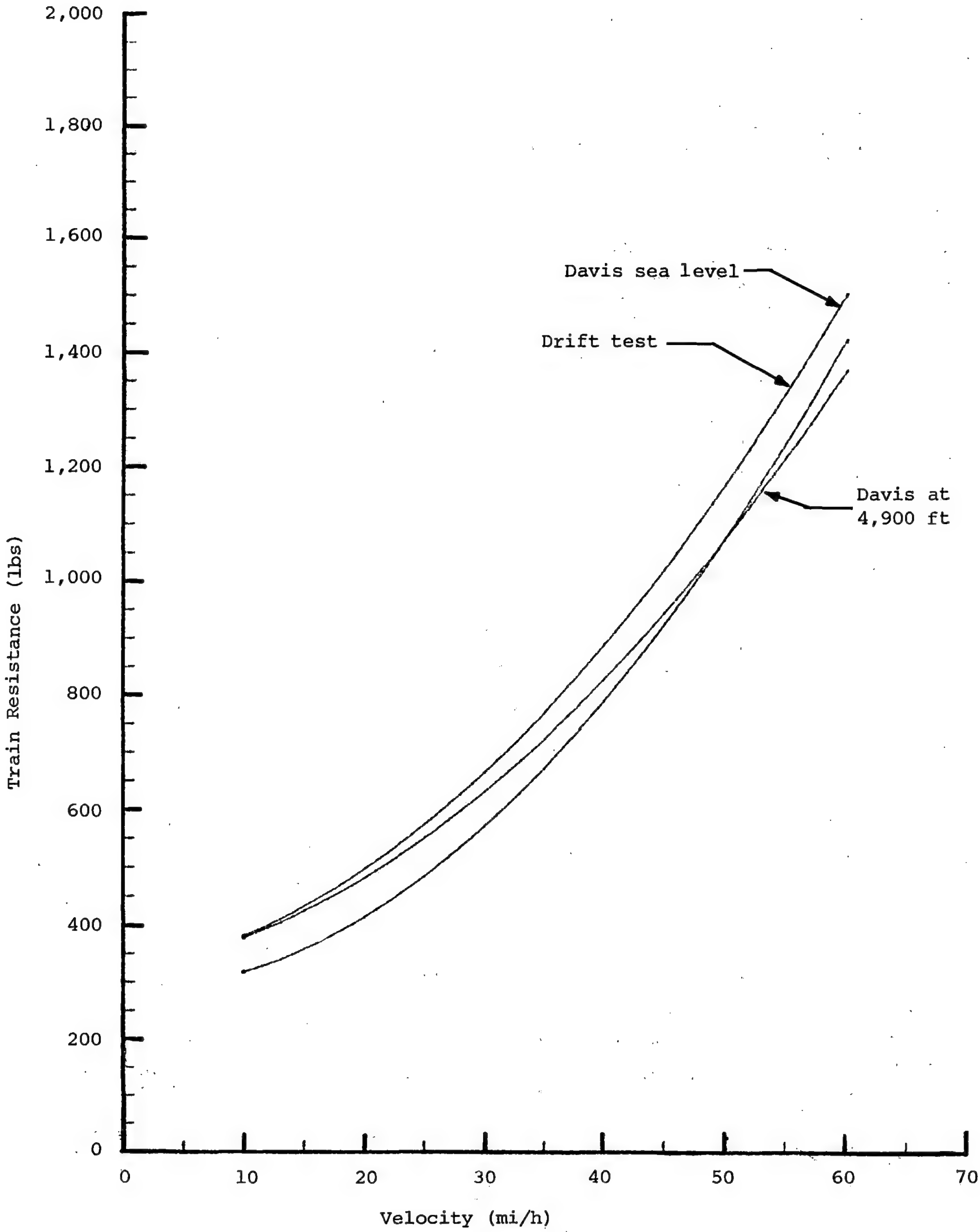

FIGURE B-3. COMPARISON OF DAVIS FORMULA (USING VEHICLE SPECIFICATION DAVIS COEFFICIENTS) AND DRIFT TEST DATA, AND AN $A_0+A_2V^2$ CURVE FIT FOR AW2 WEIGHT.

drag coefficient constitutes a major source of test error. The method of forming composite runs of CW and CCW directions to reduce wind effects is useful only at very low wind speeds.

The drift test, as performed on these cars, is suitable for estimating overall train resistance, but not for estimating the relative size of each resistance term.

APPENDIX C

TEST AND RUN NUMBER CROSS REFERENCE AND SIMULATED LINE PROFILES

This appendix contains test and run number cross reference information (tables C-1 through C-3) and the WMATA, NYCTA "A" Train, Blue Line, and ACT-1 simulated line profiles (tables C-4 through C-7).

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, GENERAL TEST PROGRAM.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
P-2001-TT	Acceleration Performance	AWO	15, 20, 35, 60	P1 - P4	Combined with Deceleration	612 - 663	6565-019	7/27/79
P-2001-TT	Acceleration Performance	AW1	10, 20, 35, 60	P1 - P4	Combined with Deceleration	1 - 50	6565-001	6/14/79
P-2001-TT	Acceleration Performance	AW2	15, 20, 35, 60	P1 - P4	Combined with Deceleration	147 - 196	6565-009	6/22/79
P-2001-TT	Acceleration Performance	AW3	15, 20, 35, 60	P1 - P4	Combined with Deceleration	265 - 314	6565-011	6/29/79
P-3001-TT	Deceleration Blended	AWO	15, 20, 35, 60	Minimum 50% Maximum	Combined with Acceleration Braking was first initiated by EP then by SAP	612 - 663	6565-019	7/29/79
P-3001-TT	Deceleration Blended	AW1	10, 20, 35, 60	Minimum 50% Maximum	Combined with Acceleration Braking was first initiated by EP then by SAP	1 - 50	6565-001	6/14/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
P-3001-TT	Deceleration Blended	AW2	15, 20, 35, 60	Minimum 50%	Combined with Acceleration Braking was first initiated by EP then by SAP	147 - 196	6565-009	6/22/79
P-3001-TT	Deceleration Blended	AW3	15, 20, 35, 60	Minimum 50% Maximum	Combined with Acceleration Braking was first initiated by EP then by SAP	265 - 314	6565-011	6/29/79
P-3002-TT	Deceleration Friction	AW0	10, 20, 35, 40	Minimum 50% Maximum	Initial Runs with EP Control. Latter Runs with SAP Control	546 - 611	6565-019	7/26/79
P-3002-TT	Deceleration Friction	AW1	10, 20, 35, 40	Minimum 50% Maximum	Initial Runs with EP Control. Latter Runs with SAP Control	496 - 543	6565-018	7/23/79
P-3002-TT	Deceleration Friction	AW2	10, 20 35, 40	Minimum 50% Maximum	Initial Runs with EP Control. Latter Runs with SAP Control	435 - 482	6565-018	7/19/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
P-3002-TT	Deceleration Friction	AW3	10, 20, 35, 40	Minimum 50% Maximum	Initial Runs with EP Control. Latter Runs with SAP Control	377 - 424	6565-108	7/18/79
P-3003-TT	Deceleration Dynamic	AW0	15, 20, 35, 60	Minimum 50% Maximum	Friction Brake System Cut-out	664 - 687	6565-019	7/27/79
P-3003-TT	Deceleration Dynamic	AW1	20, 35, 60	Minimum 50% Maximum	Friction Brake System Cut-out	51 - 68	6565-001	6/14/79
P-3003-TT	Deceleration Dynamic	AW2	15, 20, 35, 60	Minimum 50% Maximum	Friction Brake System Cut-out	197 - 220	6565-009	6/25/79
P-3003-TT	Deceleration Dynamic	AW3	15, 20, 35, 60	Minimum 50% Maximum	Friction Brake System Cut-out	315 - 338	6565-011	7/03/79
P-3004-TT	Deceleration Emergency	AW0	20, 40, 60	Emergency	Emergency initiated by deadman, M/C Pos., Conductor valve and trip cock.	554 - 563	6565-019	7/26/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
P-3004-TT	Deceleration Emergency	AW1	20, 40, 60	Emergency	Emergency initiated by deadman, M/C Pos., Conductor valve and trip cock.	544 - 553	6565-019	7/24/79
P-3004-TT	Deceleration Emergency	AW2	20, 40, 60	Emergency	Emergency initiated by deadman, M/C Pos., Conductor valve and trip cock.	438 - 492	6565-018	7/20/79
P-3004-TT	Deceleration Emergency	AW3	20, 40, 60	Emergency	Emergency initiated by deadman, M/C Pos., Conductor valve and trip cock.	425 - 434	6565-018	7/18/79
P-4001-TT	Drift Test	AW0	601/ entry	Coast	Run was made from 60 mi/h to 10 mi/h in each direction.	688 - 700	6565-019	7/30/79
P-4001-TT	Drift Test	AW1	601/ entry	Coast	Run was made from 60 mi/h to 10 mi/h in each direction.	69 - 84	6565-009	6/18/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
P-4001-TT	Drift Test	AW2	601/ entry	Coast	Run was made from 60 mi/h to 10 mi/h in each direction.	132 - 146	6565-009	6/22/79
P-5001-TT	Duty Cycle Friction Brakes	AW2	35	-	Accelerate to 35 mi/h cruise for 45 s max. brake to a stop, wait 30 s, repeat.	493	6565-018	7/20/79
P-5001-TT	Duty Cycle Friction Brakes	AW2	50	-	Accelerate to 50 mi/h cruise for 55 s max. brake to a stop, wait 30 s, repeat.	494	6565-018	7/20/79
P-5001-TT	Duty Cycle Friction Brakes	AW2	50	-	MBTA Revenue Profile with Dynamic Brakes cut-out.	495	6565-018	7/23/79
PC-5001-TT	Power Consumption	AW2	-	-	WAMATA Profile run one round trip 17.1 mi.	221	6565-009	6/25/79
PC-5001-TT	Power Consumption	AW2	-	-	NYCTA - "A" Train Profile run one round trip 21.7 mi.	222	6565-009	6/25/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
PC-5001-TT	Power Consumption	AW2	-	-	MBTA "Blue Line" Profile run one round trip 10.2 mi. Run No. 223 is not complete on tape and not used for Data Reduction.	223 224 - 225	6565-009 6565-010	6/26/79 6/26/79
PC-5001-TT	Power Consumption	AW2	-	-	ACT-1 Profile run one round trip 18.1 mi.	226	6565-010	6/29/79
R-0010-TT	Component Induced Vibration	AW1	0	-	Third Rail on all car Systems off.	123	6565-002	6/19/79
					Motor Generator on.	124		
					M.G. & Air Comp.	125		
					M.G. & Evap.	126		
					M.G. Evap. & Air Comp.	127		
					M.G. Evap. & Air Cond.	128		
					M.G., Evap., Air Comp. and Air Cond.	129		

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
R-0010-TT Cont.					Same as 129 and doors cycling.	130		
					Same as 129 and brakes cycling.	131		
R-1101-TT	Ride Roughness Worst Speed	AW1	15	-	Stn. 12 - 15 21.5 - 24 25.5 - 28 36 - 38.5 45 - 48 48 - 51 52 - 5	85 86 87 88 89 90 91	6565-002	6/15/79
		AW1	30	-	Same as above.	92 - 98	6565-002	6/15/79
		AW1	45	-	Same as above.	99 - 105	6565-002	6/15/79
		AW1	60	-	Same as above.	106 - 112	6565-002	6/15/79
R-1101-TT	Ride Roughness Worst Speed	AW2	15	-	Stn. 12 - 15 21.5 - 24 25.5 - 28	237 238 239	6565-010	6/27/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
R-1101-TT Cont.		AW3	60	-	Same as above.	370 - 376	6565-015	7/12/79
R-2001-TT	Ride Roughness Acceleration	AW1	-	P1 - P4	Each control position was for 4,000 ft of acceleration.	113 - 116	6565-002	6/18/79
R-2001-TT	Ride Roughness Acceleration	AW2	-	P1 - P4	Each control position was for 4,000 ft of acceleration.	227 - 230	6565-010	6/27/79
R-2001-TT	Ride Roughness Acceleration	AW3	-	P1 - P4	Each control position was for 4,000 ft of acceleration.	339 - 342	6565-015	7/11/79
R-3001-TT	Ride Roughness Deceleration	AW1	10, 20, 30, 40, 50, 60	Maximum	Maximum brake to a stop each speed.	117 - 122	6565-002	6/18/79
R-3001-TT	Ride Roughness Deceleration	AW2	10, 20, 30, 40, 50, 60	Maximum	Maximum brake to a stop each speed.	231 - 236	6565 - 010	6/27/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
R-3001-TT	Ride Roughness Deceleration	AW3	10, 20, 30, 40, 50, 60	Maximum	Maximum brake to a stop each speed.	343 - 348	6565-015	7/12/79
PN-1001-TT	Noise-Speed Effect on car	AW1	10, 20, 30	-	4 Microphone locations each speed.	18 - 29	6565-003	6/18/79
PN-1001-TT	Noise-Speed Effect on car	AW2	10, 20, 30, 40, 50, 60	-	4 Microphone locations each speed.	111 - 134	6565-014	6/21/79
PN-1101-TT	Noise-Speed Effect on car	AW3	10, 20, 30, 40, 50, 60	-	4 Microphone locations each speed.	178 - 201	6565-014	7/11/79
PN-1101-TT	Noise-Track Type Effect on car	AW1	60	-	Continuous lap.	61 - 67	6565-005	6/20/79
PN-1101-TT	Noise-Track Type Effect on car	AW2	60	-	Continuous lap.	104 - 110	6565-007	6/21/79
PN-1101-TT	Noise-Track Type Effect on car	AW3	60	-	Continuous lap Runs 171-177 Repeated 5 times.	171 - 177	6565-012/013	7/02/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
PN-1301-TT	Noise-Interior Survey	AW1	40	-	16 Microphone locations for survey.	76 - 91	6565-006	6/20/79
PN-1301-TT	Noise-Interior Survey	AW2	40	-	16 Microphone locations for survey.	135 - 150	6565-007	6/21/79
PN-1301-TT	Noise-Interior Survey	AW3	40	-	16 Microphone locations for survey.	202 - 217	6565-014	7/12/79
PN-2001-TT	Noise-On car Acceleration	AW1	15, 25, 35, 45	P1 - P4	2 Microphone locations Acceleration combined with Deceleration.	68 - 75	6565-005	6/20/79
PN-2001-TT	Noise-On car Acceleration	AW2	15, 25, 35, 45	P1 - P4	2 Microphone locations Acceleration combined with Deceleration.	151 - 158	6565-008	6/21/79
PN-2001-TT	Noise-On car Acceleration	AW3	15, 25, 35, 45	P1 - P4	2 Microphone locations Acceleration combined with Deceleration.	218 - 225	6565-016	7/12/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
PN-3001-TT	Noise-On car Deceleration	AW1	15, 25, 35, 45	Maximum	2 Microphone locations at each speed. Deceleration runs combined with acceleration runs.	68 - 75	6565-005	6/20/79
PN-3001-TT	Noise-On car Deceleration	AW2	15, 25, 35, 45	Maximum	2 Microphone locations at each speed. Deceleration runs combined with acceleration runs.	151 - 158	6565-008	6/21/79
PN-3001-TT	Noise-On car Deceleration	AW3	15, 25, 35, 45	Maximum	2 Microphone locations at each speed. Deceleration runs combined with acceleration runs.	218 - 225	6565-016	7/12/79
CN-0001-TT	Noise-Survey Equipment at platform	AW1	0	-	(At platform)			
					Car 0608 all off	1	6565-003	6/18/79
					M.G. on	2		
					M.G. & Air Comp. on	3		
					M.G. & Evap.	4		
					M.G., Evap, & A/C	5		
					M.G., Evap, & Air Cond	6		
					M.G., Evap, AC & A/C	7		
					All of 7 & Doors	8		
					All of 7 & Brakes	9		

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
CN-0001-TT Cont.					Repeat 1, 2, 4, 5, 6, 7, 8, & 9 for car 0609	10 - 17		
CN-0001-TT	Noise Survey Equipment at Wayside	AW1	0	-	(50 ft Wayside) Repeat of 1 through 9 Center of train right side.	30 - 36	6565-004	6/18/79
CN-1001-TT	Noise-Speed Effect Way-side	AW1	20, 30, 40, 50, 60	-	All readings taken 50 ft from track left side.	37 - 42	6565-004	6/20/79
CN-1001-TT	Noise-Speed Effect Way-side	AW1	20, 30, 40, 50, 60	-	All readings taken 50 ft from track right side.	43 - 48	6565-004	6/20/79
CN-1001-TT	Noise-Speed Effect Way-side	AW2	20, 30, 40, 50, 60	-	Readings made from both sides.	92 - 103	6565-007	6/21/79
CN-1001-TT	Noise-Speed Effect Way-side	AW3	20, 30, 40, 50, 60	-	Readings made from both sides.	159 - 170	6565-012	7/02/79

TABLE C-1. TEST AND RUN NUMBER CROSS REFERENCE, CONTINUED.

TEST SET	TITLE	WEIGHT	SPEED MI/H	CONTROLLER POSITION	COMMENTS	RUN NUMBERS	TAPE NO.	TEST DATE
CN-1001-TT	Noise-Speed Effect Way-side	AW3	20, 30, 40, 50, 60	-	Readings made from both sides with traction motor shrouds installed	226 - 235	6565-017	7/17/79

TABLE C-2. TEST AND RUN NUMBER CROSS-REFERENCE, ENERGY CONSERVATION TEST PROGRAM.

TEST OPTION	COMMENTS	WEIGHT	CUT-OUT SPEED	RESET BANDWIDTH	RUN NUMBERS	TAPE NO.	TEST DATE
Control	Acceleration rate set at 2.5 mi/h/s. Deceleration rate set at 2.75 mi/h/s. All other parameters normal. Runs were made with controller in P4 until braking time then maximum brake was used.	AW3	40	2	25 - 31	6565-024	10/17/79
1	Acceleration rate set at 3.0 mi/h/s. Deceleration rate set at 3.0 mi/h/s. All other parameters normal. Controller level P4 and maximum brake used.	AW3	37	4	32 - 37	6565-025	10/19/79
2	Acceleration rate set at 3.0 mi/h/s. Deceleration rate set at 3.0 mi/h/s. All other parameters normal. Controller level P4 and maximum brake used.	AW3	34	4	38 - 42	6565-025	10/22/79
3	Acceleration rate set at 3.0 mi/h/s. Deceleration rate set at 3.0 mi/h/s. All other parameters normal. Controller level P4 and maximum brake used.	AW3	31	4	50 - 52 53 - 55	6565-026 6565-027	10/24/79 10/24/79

TABLE C-2. TEST AND RUN NUMBER CROSS-REFERENCE, ENERGY CONSERVATION TEST PROGRAM, CONTINUED.

TEST OPTION	COMMENTS	WEIGHT	CUT-OUT SPEED	RESET BANDWIDTH	RUN NUMBERS	TAPE NO.	TEST DATE
4	Acceleration rate set at 3.0 mi/h/s. Deceleration rate set at 3.0 mi/h/s. All other parameters normal. Controller level P4 and maximum brake used.	AW3	37	8	56 - 61	6565-027	10/25/79
5	Acceleration rate set at 3.0 mi/h/s. Deceleration rate set at 3.0 mi/h/s. All other parameters normal. Controller level P4 and maximum brake used.	AW3	37	12	62 - 67	6565-028	10/26/79
6	Acceleration rate set at 3.0 mi/h/s. Deceleration rate set at 3.0 mi/h/s. Propulsion field shunts inoperative. All other parameters normal. Controller level P4 and maximum brake used.	AW3	37	4	68 - 71	6565-028	10/29/79
					72	6565-029	10/31/79
Maximum Accelera-tion	Acceleration rate set 3.0 mi/h/s. Each run consisted of ten (5 in each direction) runs using P4 to cut-out speed. The cut-out speed was readjusted after each 10 runs series, starting at 40 mi/h and decreasing in one mile per hour increments to 30 mi/h; the reset bandwith was not used.	AW3	40, 39, 38, 37, 36, 35, 34, 33, 32, 31, 30	-	73 - 83	6565-029	10/31/79

TABLE C-3. TEST AND RUN NUMBER CROSS-REFERENCE, BRAKE SHOE TEST PROGRAM.

SHOE TYPE	COMMENTS	TYPE BRAKING	SHOE CONDITION	WEIGHT	SPEED	RUN NUMBER	TAPE NUMBER	TEST DATE
WABCO W-392	A Base Line Test was conducted on this shoe type first as the shoe is normally installed. Second with a rubber shim between the brake shoe and actuator. These runs were not recorded on tape. However, the data recorded during the GVTP is the same. The tape and test numbers referenced at right are from GVTP Test sets P-3002-TT and P-3002-TT. NOTE: As these runs were rerun they were number 1 through 96 for Brake Test.		Partially Worn	AW0	10, 20, 35, 60	564 - 663	6565-019	7/26/79 7/27/79
				AW3	10, 20, 35, 60	265 - 314	6565-011	6/29/79
						377 - 424	6565-018	7/17/79
WABCO W-539	Shoe was 100% seated prior to start of test.	Dynamic	New	AW0	15, 25, 35, 45, 55, 65	97 - 120	6565-020	8/21/79
WABCO W-539	Shoe was 100% seated prior to start of test.	Friction	New	AW0	15, 25, 35, 45, 55, 65	121 - 144	6565-020	8/22/79

TABLE C-3. TEST AND RUN NUMBER CROSS-REFERENCE, BRAKE SHOE TEST PROGRAM, CONTINUED.

SHOE TYPE	COMMENTS	TYPE BRAKING	SHOE CONDITION	WEIGHT	SPEED	RUN NUMBER	TAPE NUMBER	TEST DATE
WABCO W-539	Shoe was 100% seated prior to start of test.	Dynamic	New	AW3	15, 25, 35, 45, 55, 65	145 - 168	6565-020	8/24/79
WABCO W-539	Shoe was 100% seated prior to start of test.	Friction	New	AW3	15, 25, 35, 45, 55, 65	169 - 192	6565-020	8/24/79
WABCO W-539	Shoes were machined to a half worn thickness and 100% re-seated prior to start of test.	Dynamic	Half/Worn	AW3	15, 25, 35, 45, 55, 65	385 - 408	6565-021	9/20/79
WABCO W-539	Shoes were machined to a half worn thickness and 100% re-seated prior to start of test.	Friction	Half/Worn	AW3	15, 25, 35, 45, 55, 65	409 - 432	6565-021	9/24/79
WABCO W-539	Shoes were machined to a half worn thickness and 100% re-seated prior to start of test.	Dynamic	Half/Worn	AW0	15, 25, 35, 45, 55, 60	433 - 456	6565-021	9/25/79
WABCO W-539	Shoes were machined to a half worn thickness and 100% re-seated prior to start of test.	Friction	Half/Worn	AW0	15, 25, 35, 45, 55, 60	457 - 480	6565-021	9/25/79

TABLE C-3. TEST AND RUN NUMBER CROSS-REFERENCE, BRAKE SHOE TEST PROGRAM, CONTINUED.

SHOE TYPE	COMMENTS	TYPE BRAKING	SHOE CONDITION	WEIGHT	SPEED	RUN NUMBER	TAPE NUMBER	TEST DATE
WABCO W-539	Shoes were machined to a half worn thickness and 100% re-seated prior to start of test.	Emergency	Half/Worn	AW0	40	481 - 482	6565-021	9/25/79
ABEX T-176-4	New shoes were installed and 100% seated prior to start of test.	Dynamic	New	AW3	15, 25, 35, 45, 55, 65	193 - 216	6565-020	9/04/79
ABEX T-176-4	New shoes were installed and 100% seated prior to start of test.	Friction	New	AW3	15, 25, 35, 45, 55, 65	217 - 240	6565-020	9/05/79
ABEX T-176-4	New shoes were installed and 100% seated prior to start of test.	Dynamic	New	AW0	15, 25, 35, 45, 55, 65	241 - 264	6565-020	9/06/79
ABEX T-176-4	New shoes were installed and 100% seated prior to start of test.	Friction	New	AW0	15, 25, 35, 45, 55, 65	265 - 288	6565-020	9/07/79
ABEX T-176-4	The brake shoes were machined to a half worn thickness and 100% seated prior to start of test.	Dynamic	Half/Worn	AW0	15, 25, 35, 45, 55, 65	483 - 506	6565-021	9/28/79

TABLE C-3. TEST AND RUN NUMBER CROSS-REFERENCE, BRAKE SHOE TEST PROGRAM, CONTINUED.

SHOE TYPE	COMMENTS	TYPE BRAKING	SHOE CONDITION	WEIGHT	SPEED	RUN NUMBER	TAPE NUMBER	TEST DATE
ABEX T-176-4	The brake shoes were machined to a half worn thickness and 100% seated prior to start of test.	Friction	Half/Worn	AW0	15, 25, 35, 45, 55, 65	507 - 530	6565-021	9/28/79
ABEX T-176-4	The brake shoes were machined to a half worn thickness and 100% seated prior to start of test.	Emergency	Half/Worn	AW0	15, 25, 35, 45, 55, 65	531 - 532	6565-021	9/28/79
ABEX T-176-4	The brake shoes were machined to a half worn thickness and 100% seated prior to start of test.	Dynamic	Half/Worn	AW3	15, 25, 35, 45, 55, 65	533 - 556	6565-021	10/01/79
ABEX T-176-4	The brake shoes were machined to a half worn thickness and 100% seated prior to start of test.	Friction	Half/Worn	AW3	15, 25, 35, 45, 55, 65	557 - 580	6565-021	10/01/79 10/01/79
ABEX T-176-4	The brake shoes were machined to a half worn thickness and 100% seated prior to start of test.	Emergency	Half/Worn	AW3	40	581 - 582	6565-021	10/01/79

TABLE C-3. TEST AND RUN NUMBER CROSS-REFERENCE, BRAKE SHOE TEST PROGRAM, CONTINUED.

SHOE TYPE	COMMENTS	TYPE BRAKING	SHOE CONDITION	WEIGHT	SPEED	RUN NUMBER	TAPE NUMBER	TEST DATE
Griffin Anchor	New brake shoes were installed and 100% seated prior to start of test.	Dynamic	New	AW0	15, 25, 35, 45, 55, 65	289 - 312	6565-021	9/12/79
Griffin Anchor	New brake shoes were installed and 100% seated prior to start of test.	Friction	New	AW0	15, 25, 35, 45, 55, 65	313 - 336	6565-021	9/13/79
Griffin Anchor	New brake shoes were installed and 100% seated prior to start of test.	Dynamic	New	AW3	15, 25, 35, 45, 55, 65	337 - 360	6565-021	9/14/79
Griffin Anchor	New brake shoes were installed and 100% seated prior to start of test.	Friction	New	AW3	15, 25, 35, 45, 55, 65	361 - 384	6565-021	9/17/79
Griffin Anchor	The brake shoes were machined to half worn thickness and 100% seated prior to start of test.	Dynamic	Half/Worn	AW3	15, 25, 35, 45, 55, 65	583 - 606	6565-021	10/03/79
Griffin Anchor	The brake shoes were machined to half worn thickness and 100% seated prior to start of test.	Friction	Half/Worn	AW3	15, 25, 35, 45, 55, 65	607 - 630	6565-022	10/03/79

TABLE C-3. TEST AND RUN NUMBER CROSS-REFERENCE, BRAKE SHOE TEST PROGRAM, CONTINUED.

SHOE TYPE	COMMENTS	TYPE BRAKING	SHOE CONDITION	WEIGHT	SPEED	RUN NUMBER	TAPE NUMBER	TEST DATE
Griffin Anchor	The brake shoes were machined to half worn thickness and 10% seated prior to start of test.	Emergency	Half/Worn	AW3	40	631 - 632	6565-022	10/03/79
Griffin Anchor	The brake shoes were machined to half worn thickness and 10% seated prior to start of test.	Dynamic	Half/Worn	AW0	15, 25, 35, 45, 55, 65	633 - 656	6565-022	10/04/79
Griffin Anchor	The brake shoes were machined to half worn thickness and 100% seated prior to start of test.	Friction	Half/Worn	AW0	15, 25, 35, 45, 55, 65	657 - 680	6565-022	10/04/79
Griffin Anchor	The brake shoes were machined to half worn thickness and 100% seated prior to start of test.	Emergency	Half/Worn	AW0	40	681 - 682	6565-022	10/04/79

TABLE C-4. WMATA SIMULATED LINE PROFILE, GROSVENOR TO METRO CENTER, SILVER SPRING TO METRO CENTER.

TIME AT START	START STATION	DIRECTION	ACCEL. TO (mi/h)	CHANGE TO NEXT SPEED AT TIME	NEXT SPEED (mi/h)	CHANGE TO NEXT SPEED AT TIME	NEXT SPEED (mi/h)	CHANGE AT	NEXT SPEED (mi/h)
0	30	N	70	1:05	60	1:36	0		
2:19	38.7	S	70	3:26	50	3:46	0		
4:24	30.9	N	75	5:42	0				
6:32	39.1	S	60	7:16	50	7:30	0		
8:08	34.2	N	40	8:37	60	9:07	40	9:50	0
10:24	41.0	S	50	10:58	0				
11:36	38.4	S	60	12:20	0				
13:03	34.2	N	70	14:06	0				
14:54	40.08	S	50	15:30	0				
16:08	37.9	S	50	17:01	0				
17:40	33.8	N	75	19:22	0				
20:13	44.3	S	75	21:48	0				
22:39	33.7	N	70	23:49	55	24:0	0		
24:40	41.1	S	60	25:31	55	25:36	0		

TABLE C-4. WMATA SIMULATED LINE PROFILE, GROSVENOR TO METRO CENTER, SILVER SPRING TO METRO CENTER, CONTINUED.

TIME AT START	START STATION	DIRECTION	ACCEL. TO (mi/h)	CHANGE TO NEXT SPEED AT TIME	NEXT SPEED (mi/h)	CHANGE TO NEXT SPEED AT TIME	NEXT SPEED (mi/h)	CHANGE AT	NEXT SPEED (mi/h)
26:14	36.0	S	75	27:23	65	27:53	0		
28:38	25.9	N	40	29:07	45	29:16	40	29:34	0
30:07	29.3	N	45	30:34	0				
31:10	31.0	N	40	31:33	0				

NOTE: Top speed of MBTA cars is 65 mi/h. Where indicated speed could not be achieved, maximum acceleration (P4) was used for time specified.

TABLE C-5. NYCTA "A" TRAIN, SIMULATED RUN PROFILE.

START STATION	STATION MARKER	MAX SPEED (mi/h)	STOP STATION	STATION MARKER
1. 207th St.	52.100	40	2	49.900
2. 200th St.	49.900	50	3	46.800
3. 190th St.	46.800	50	4	4.100
4. 181th St.	44.100	45	5	42.300
5. 175th St.	42.300	30	6	39.700
6. 168th St.	39.700	40	7	33.600
7. 145th St.	33.600	50	8	28.100
8. 125th St.	28.100	50	9	10.400
9. 59th St.	10.400	50	10	5.600
10. 42th St.	5.600	35	11	51.900
11. 34th St.	51.900	50	12	47.200
12. 14th St.	47.200	45	13	43.800
13. 4th St.	43.800	50	14	39.500
14. Canal St.	39.500	45	15	36.700
15. Chambers St.	36.700	30	16	34.800
16. Broadway	34.800	50	17	28.400
17. Brooklyn Brg.	28.400	35	18	25.200
18. Jay St.	25.200	25	19	23.200
19. Hoyt St.	23.200	30	20	20.000
20. Lafayette Ave.	20.000	35	21	17.500
21. Clinton Ave.	17.500	40	22	14.900
22. Franklin Ave.	14.900	40	23	13.000
23. No Strand Ave.	13.000	35	24	10.400

TABLE C-5. NYCTA "A" TRAIN SIMULATED RUN PROFILE, CONTINUED.

START STATION	STATION MARKER	MAX SPEED (mi/h)	STOP STATION	STATION MARKER
24. Throop Ave.	10.400	35	25	7.600
25. Utica Ave.	7.600	35	26	4.900
26. Ralph Ave.	4.900	35	27	50.600
27. Rockaway Ave.	50.600	40	28	48.800
28. E. New York St.	48.800	25	29	45.600
29. Liberty Ave.	45.600	35	30	43.200
30. Van Sicien Ave.	43.200	40	31	40.500
31. Shepard Ave.	40.500	35	32	38.200
32. Euclid Ave.	38.200	25	33	35.900
33. Grant Ave.	35.900	35	34	34.000
34. Hudson St.	34.000	35	35	31.900
35. Boyd Ave.	31.900			

TABLE C-6. MBTA BLUE LINE SIMULATED PROFILE.

DEPART STATION	TRACK STATION	TIME START	SPEED (mi/h)	TIME	NEXT SPEED (mi/h)	TIME	NEXT SPEED (mi/h)	TIME	NEXT SPEED (mi/h)	TIME	NEXT SPEED (mi/h)
BOWDIN	25	0:00	15	0:43	0						
GOVERNMENT CTR.	25.9	1:13	15	1:54	0						
STATE	26.8	2:24	40	2:58	0						
AQUARIUM	28.3	3:40	40	4:55	0						
MAVERICK	33	5:49	35	6:35	15	6:52	0				
AIRPORT	35.5	7:29	25	8:12	30	8:20	35	8:26	0		
WOOD ISLAND	38	9:10	30	10:15	40	10:40	0				
ORIENT HEIGHTS	42.6	11:29	10	11:40	20	11:54	30	12:22	0		
SUFFOLK DOWNS	44.9	13:07	30	14:00	0						
BEACHMONT	47.4	14:47	40	15:40	0						
REVERE BEACH	50.5	16:24	35	16:44	30	16:58	10	17:16	0		
WONDERLAND	52:2	19:16	35	19:47	20	19:58	0				
REVERE BEACH	50.5	20:30	35	21:19	20	21:44	0				
BEACHMONT	47.3	22:24	30	23:17	0						

TABLE C-6. MBTA BLUE LINE SIMULATED PROFILE, CONTINUED.

DEPART STATION	TRACK STATION	TIME START	SPEED (mi/h)	TIME	NEXT SPEED (mi/h)	TIME	NEXT SPEED (mi/h)	TIME	NEXT SPEED (mi/h)	TIME	NEXT SPEED (mi/h)
SUFFOLK DOWNS	44.9	24:01	20	25:10	0						
ORIENT HEIGHTS	42.6	25:50	40	27:03	0						
WOOD ISLAND	38.1	27:53	25	28:08	35	28:12	30	28:28	35	28:45	0
AIRPORT	35.4	29:35	30	30:03	20	30:24	0				
MAVERICK	33	31:05	13	31:24	30	32:15	40	32:38	0		
AQUARIUM	28.3	33:29	25	34:02	0						
STATE	26.8	34:45	13	35:10	10	35:30	0				
GOVERNMENT CTR.	25.8	36:05	15	36:45	0						

TABLE C-7. ACT-1, SIMULATED LINE PROFILE.

START STATION	STATION MARKER	MAXIMUM SPEED (mi/h)	STOP STATION	STATION MARKER
A	52.170	60	B	7.960
B	7.960	70*	C	13.250
C	13.250	50	D	15.800
D	15.800	60	E	19.840
E	19.840	50	F	22.450
F	22.450	40	G	23.860
G	23.860	40	H	25.120
H	25.120	50	I	27.760
I	27.760	80*	J	35.680
J	35.680	80*	K	42.280
K	42.280	40	L	43.600
L	43.600	50	M	46.240
M	46.240	40	N	47.560
N	47.560	70*	O	52.840
O	52.840	70*	N	47.560
N	47.560	40	M	46.240
M	46.240	50	L	43.600
L	43.600	40	K	42.280
K	42.280	80*	J	35.680
J	35.680	80*	I	27.760
I	27.760	50	H	25.120

* Top speed of the MBTA cars was 65 mi/h. Where the maximum required speed could not be achieved, maximum (P4) acceleration was used to 65 mi/h.

TABLE C-7. ACT-1, SIMULATED LINE PROFILE, CONTINUED.

Start Station	Station Marker	Maximum Speed (mi/h)	Stop Station	Station Marker
H	25.120	40	G	23.860
G	23.860	40	F	22.450
F	22.450	50	E	19.840
E	19.840	60	D	15.800
D	15.800	50	C	13.250
C	13.250	70*	B	7.960
B	7.960	60	A	52.170

* Top speed of the MBTA cars was 65 mi/h. Where the maximum required speed could not be achieved, maximum (P4) acceleration was used to 65 mi/h.

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